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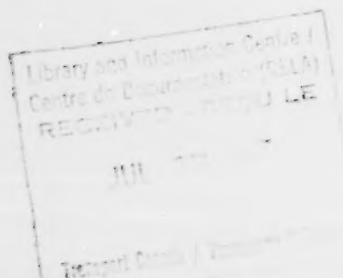
MANOEUVRING TESTS IN ICE
ABOARD USCGC POLAR STAR IN ANTARCTICA 1985

TP 8297E

OCTOBER 1986

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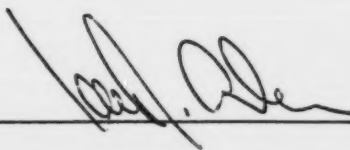
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17. Abstract This report describes a comprehensive program of assessment of the manoeuvring performance of POLAR CLASS vessels involving full-scale, level ice turning trials as well as development of mathematical models to predict steady turning radius. The trials were carried out in McMurdo Sound, Antarctica, which generated 19 data points. Two mathematical models were developed, one making use of a time history method utilizing approximate model test data for hull coefficients. The second model makes use of a force balance method involving an assumed hull-side force distribution. Preliminary comparisons of the predicted and measured turning radii have been made. Analysis of the full-scale data showed that further controlled tests at larger rudder angles will be required for complete validation of the mathematical models.		
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SUMMARY

The 1985 summer Antarctic Deployment of USCGC POLAR STAR provided an opportunity to obtain full scale manoeuvring performance data in level ice. McMurdo Sound in the Antarctic affords one of the best natural sites in the world for the conduct of level icebreaking tests. The dedicated manoeuvring tests were planned with the main objective of quantifying the manoeuvring capability of the POLAR Class vessels in ice with ship speed and rudder angle as parameters. Additional objectives were:

- ° to address the need for full scale data to assist in the development and validation of numerical models of vessel manoeuvring in ice,
- ° to develop and demonstrate a standard methodology for the conduct of full scale icebreaking manoeuvring tests including a standard data acquisition and processing system.

The shipboard instrumentation and digital data acquisition system recorded basic propulsion and steering parameters. Throughout the manoeuvring tests, the ship's position was determined once per second by measuring the ranges from the ship to two shore-fixed base stations, using a commercial microwave positioning system capable of sub-metre range resolution.

The ice sheet was level, undisturbed and gradually varying in thickness from 0.9m to 1.8m; but it was close to melting point and of low strength.

The manoeuvring tests of the POLAR STAR were conducted as a series of "S" turns, that is arcs or sectors of about 180°, executed back to back. Throughout each such arc, the propeller pitch order and the rudder angle were held constant at the desired level until the required change in heading had been obtained. Three separate sets of turning manoeuvres were conducted by the USCGC POLAR STAR during this deployment; a total of nineteen data points were recorded, each including the radius of the turning arc achieved along with the specific individual set of values of propulsion and steering parameters pertinent thereto.

Results generally confirmed predictable trends as to the effect of rudder angle, power level, and ice thickness on turning radius. They were somewhat clouded by an inability to maintain a thrust balance between the two wing propellers, and by port turns being very substantially sharper than those to starboard, under similar conditions.

A numerical model of a time domain manoeuvring simulation is presented, and using coefficients from model tests, is tested against the full scale results. It has limitations which prevent it taking sufficient account of prevailing circumstances, and was unable to provide a useful prediction.

A mathematical model based on simplified hull form and physical assumption is also presented and exercised and tested against full scale data. This model, although rather sensitive to some input values, produced a prediction which was bracketed by the differential between port and starboard turns.

SOMMAIRE

Le périple effectué dans l'Antarctique à l'été de 1985 par le brise-glace américain POLAR STAR a fourni l'occasion d'effectuer des manoeuvres giratoires dans des glaces d'épaisseur uniforme. Le détroit McMurdo se distingue des autres plans d'eau du monde par l'uniformité de l'épaisseur des glaces qui le recouvrent. Les manoeuvres qui ont été prévues pour profiter de cette occasion visaient à caractériser les qualités manoeuvrières des navires de même classe dans les glaces, en fonction de la vitesse et de l'angle de braquage. D'autres objectifs ont été fixés à ces essais, à savoir:

- i) obtenir de l'information en vraie grandeur aidant à la mise au point et à la validation des modèles numériques de simulation;
- ii) mettre au point et à l'essai une méthode pour la conduite de manoeuvres in situ dans des glaces, et notamment la chaîne de mesure utilisée pour la saisie et le traitement des données.

La chaîne de mesure numérique installée à bord du brise-glace a enregistré les principaux paramètres du système propulsif et de l'appareil à gouverner tandis que, tout au long des manoeuvres, la position du navire était repérée une fois par seconde par rapport à deux stations fixes, à l'aide d'un système de radio-localisation hyperfréquences, capable d'une résolution inférieure au mètre.

Quant à la couverture de glace, intacte tout au long, elle était uniforme mais augmentant progressivement de 0,9 à 1,8 m. Sa résistance était faible du fait qu'elle était proche du point de fusion.

Le POLAR STAR a effectué une série de girations en S, c'est-à-dire des demi-cercles ou à peu près, en vis-à-vis. Tout au long de ces manoeuvres, le pas de l'hélice ainsi que l'angle de braquage ont été gardés constants, jusqu'à ce que le changement de cap voulu soit obtenu. Trois batteries de manoeuvres ont été effectuées par le navire. Un total de 19 points de mesure ont été obtenus, à l'égard desquels les paramètres de fonctionnement relatifs au système propulsif et à l'appareil à gouverner ont été mesurés, ainsi que le rayon de braquage.

Les résultats ont, dans l'ensemble, confirmé l'influence prédite des différents paramètres en jeu sur ce rayon: angle de braquage, niveau de puissance, épaisseur des glaces. Mais ces résultats ont été quelque peu obscurcis par l'inégalité observée dans la poussée fournie par les deux hélices latérales et aussi par le fait que les girations à bâbord ont été plus prononcées que celles à tribord, toutes choses étant égales par ailleurs.

Le rapport présente un modèle de simulation pas-à-pas, fondé sur les coefficients tirés d'essais sur maquette antérieurs, et dont les résultats théoriques ont été confrontés à ceux tirés des essais in situ. Les lacunes observées et l'imprécision de ces résultats sont attribuables à son inaptitude à s'adapter aux conditions réelles des essais.

Le rapport présente en outre un autre modèle, mathématique celui-là, fondé sur des formes géométriques schématisées et sur des hypothèses simplifiées. Les résultats du modèle ont été confrontés à ceux des essais in situ. Il a été constaté que, malgré sa sensibilité à certaines valeurs d'entrée, ce modèle a donné des valeurs de rayon de braquage s'intercalant entre les valeurs obtenues des girations à bâbord et celles des girations à tribord.

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NOMENCLATURE

C	Centre shaft thrust as a percentage of total
H	Ice thickness in mathematical model
h_i	Ice thickness
l_c	Effective parallel midbody
L	Length of ship in waterline
P	Port shaft thrust as a percentage of total thrust
R/L	Turning radius
S	Starboard shaft thrust as a percentage of total thrust
T_{total}	Total shaft thrust
V	Ship's speed
δ	Rudder angle, degrees

1. INTRODUCTION

1.1 Background

To date only very limited work has been carried out to develop a physical understanding of the processes which control the manoeuvring characteristics of ice-going vessels. The development of reliable modelling techniques for manoeuvring in ice would represent a major advance useful in the design of new ice class vessels and in the simulation of their navigating characteristics for both economic and operational purposes. One of the problems in carrying forward this line of development is the scarcity of full scale data in a form that can be directly used to evaluate the various aspects of such models.

Measuring the manoeuvring performance of icebreakers at full scale has presented a number of important problems, particularly for ships whose deployments take them primarily into the North American Arctic. In these regions extensive ridging of the sea ice is common making it difficult to find the large expanses of uniform level ice which are needed to execute turning circle arcs of 180 degrees or more. Although extensive data on the trafficability of vessels in ridged sea ice fields has been obtained, it is difficult to use such data to develop the understanding of the ship-ice interaction during turning which is a necessary first step toward the construction of physically correct models of this process.

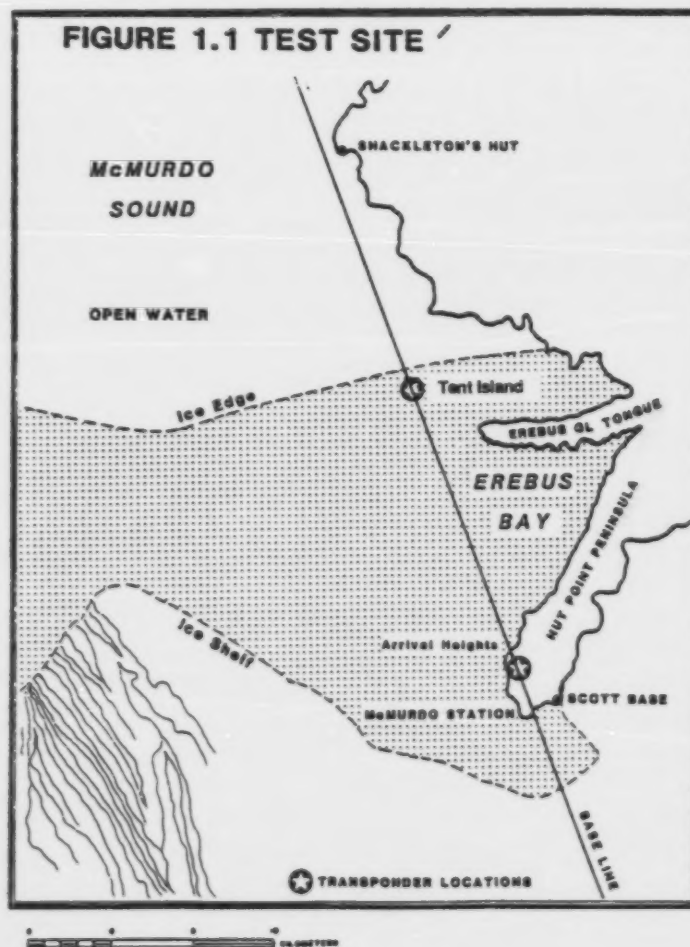
It was recognized that the annual deployment of a Polar Class icebreaker to McMurdo Sound in the Antarctic presented a unique opportunity to obtain full scale manoeuvring data in an ideal ice environment (see Figure 1.1). As part of this deployment, a series of straight-ahead icebreaking dynamics tests were also undertaken which are reported in [5]. McMurdo Sound affords one of the best natural sites in the world for the conduct of level icebreaking tests of all kinds. At the time of the ship's arrival, the Sound typically contains more than 259 km² of level, ridge-free shorefast ice, varying smoothly from about 1.8 m in thickness at the south end of the Sound to about .9 m in thicknesses available to test in are nearly twice those in the Baltic and, unlike the shallow shorefast ice regions of the Beaufort Sea, there is ample water depth for navigation of even the largest vessels throughout the Sound.

1.2 Objectives

The primary objective of the project was to carry out manoeuvring tests in the uniform level ice of McMurdo Sound, Antarctica. As part of the same project a manoeuvring performance predictor was also to be developed and evaluated in conjunction with full scale tests. The program of full scale manoeuvring tests for the 1985 deployment of the USCGC "POLAR STAR" was prepared to address the need for full scale data to assist in the development of the manoeuvring model. The objectives of this program are summarized:

- ° Quantify the manoeuvring capability of the POLAR class vessels in ice as a function of ship speed and rudder angle in .9 to 1.8 m of level first year ice.
- ° Obtain manoeuvring data for the POLAR class vessels in a form useable in the development and verification of a manoeuvring simulation model.
- ° Develop and demonstrate a standard methodology for the conduct of full scale icebreaking manoeuvring tests, including a standard data collection and process system.

In addition to the above objectives, the original test plan also called for the measurement of the ability of the vessel to turn using successive ahead/astern manoeuvres and its ability to turn out of its pre-broken channel. Due to operational concerns about the loads that such manoeuvres might impose on the wing propellers and limited dedicated ship time available for testing, these latter tests were not performed. Further, no tests were conducted with the vessel heeled and no attempts were made to manoeuvre with the wing screws. All the above decisions were taken onboard the vessel with full participation of the operations personnel, the TDC project officer and ACL test team.



2. INSTRUMENTATION AND DATA ACQUISITION SYSTEM

2.1 General

The shipboard instrumentation used to measure and record the parameters relevant to the vessel's manoeuvring performance is shown schematically in Figure 2.1. A total of nine time varying parameters were logged on a common time base by a digital data acquisition system at the rate of one scan of all channels per second. In addition the absolute time from the computer's system clock was read at the end of each scan of the input channels and this time was stored with the data to ensure the accurate time positioning of successive scans.

The parameters recorded were the following:

1. Port Propeller Shaft Thrust
2. Centre Propeller Shaft Thrust
3. Starboard Propeller Shaft Thrust
4. Ship's Speed
5. Ship's Heading
6. Rate of Change of Ship's Heading
7. Rudder Angle
8. Range to Arrival Heights Positioning Base Station
9. Range to Tent Island Positioning Base Station
10. Time of End of Scan.

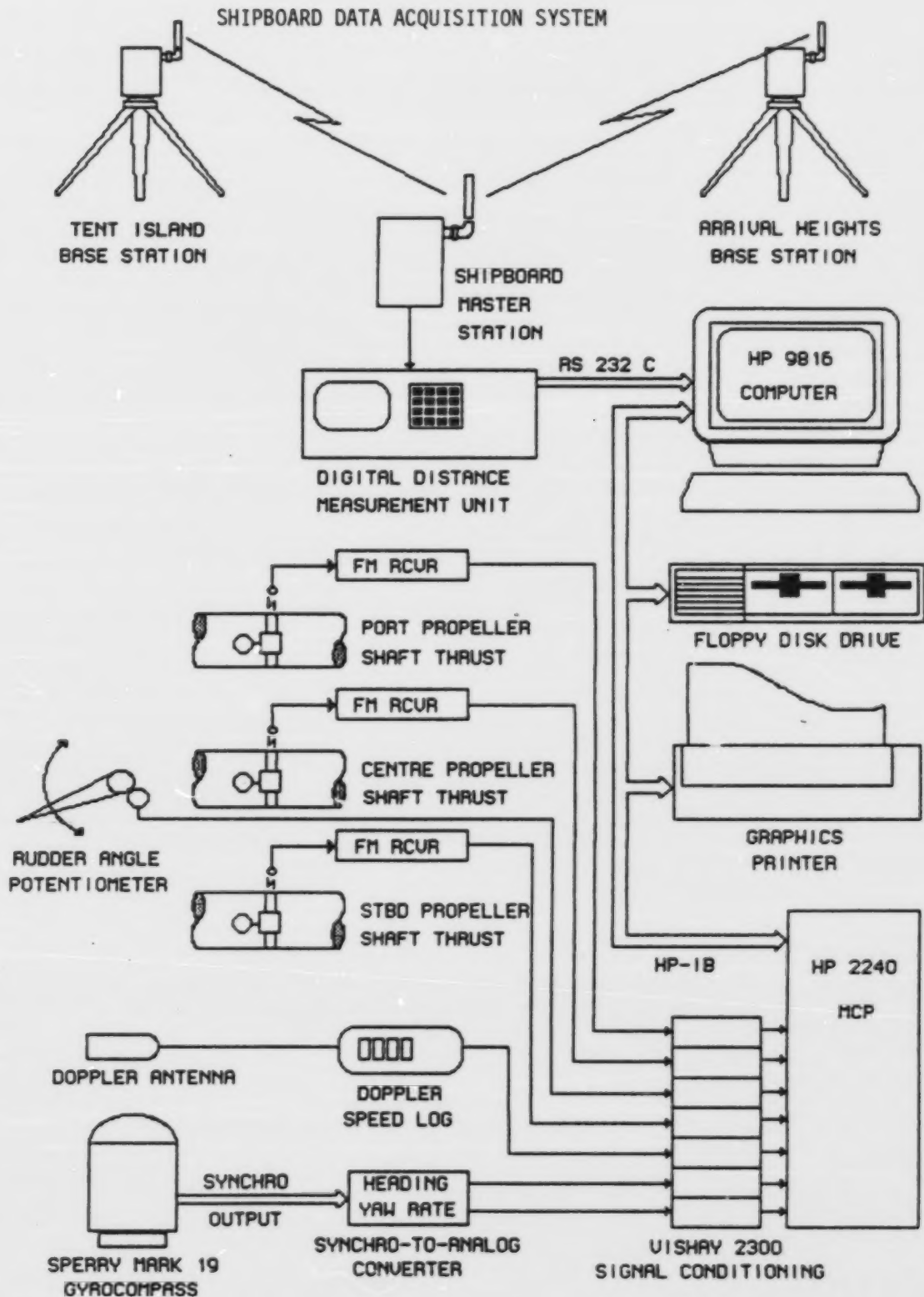
Other parameters specified in the work statement such as the rigid body motions, heel angle and shaft rpm were simultaneously recorded by Arctec Inc. team (U.S. contractor) as part of their data acquisition efforts. Attempts were made using photography from helicopter overflights. The entire instrumentation system was integrated with that set up the U.S. contractor and redundancy was ensured for major items such as position fixing system and doppler speed log. The above set up was approved by the TDC project officer prior to starting the data acquisition task.

2.2 Ship Powering and Motion Signals

The first seven parameters were available as analog signals from a variety of transducers and interfaces installed in the ship specifically for these tests. These signals were again adjusted and filtered in instrumentation signal conditioning and fed to the data acquisition computer HP9816. This unit performed sequential multiplexing and analog-to-digital conversion of the input signals and transmitted the resulting digital data to the central memory of the computer.

The three shaft thrust signals were measured using strain gauge bridges and signal conditioning mounted on the propeller shafts between the main thrust bearings and the stern tubes. These signals were removed from the rotating pieces as FM analog data via short-range radio telemetry.

FIGURE 2.1



The ship's speed was measured using a doppler microwave speed log of the type used in highway traffic control. The antenna of this unit was mounted outboard of the ship's rail at the main deck level and oriented so that its beam would be reflected back from the surface of the ice through which the ship was moving, thereby measuring the relative speed between the two.

This portion of the instrumentation was the same system as that used in the icebreaking dynamics tests and is further discussed in detail in a separate report [3].

In addition to the thrust and ship speed signals, a synchro-to-analog converter was fitted to one of the synchro outputs of the ship's Sperry Mark 19 Gyrocompass. This unit provided two output analog signals, one proportional to the ship's absolute heading relative to true north, and one proportional to the rate of change of heading (rate of yaw).

A final analog input was provided by a multi-turn potentiometer driven by the movement of the ship's rudder to yield an output proportional to the rudder angle. This signal was calibrated by reading both the mechanical setting of the rudder and the output from the potentiometer at a number of rudder settings spanning its full range of travel.

2.3 Position Fixing System

Throughout the manoeuvring tests the ship's position was determined once per second by measuring the ranges from the ship to two shore-fixed base stations. The equipment used was a commercial microwave positioning system operating near 9.4 Gigahertz and capable of sub-metre range resolution. The system was comprised of three light-weight portable radio transponders; a master unit installed on the ship above the bridge, and one tripod-mounted slave unit, powered by batteries, at each of the two shore locations.

Such a system operates by transmitting a sub-microsecond pulse of microwave radiation from the master unit which is detected by the remote slave unit. After a brief and highly stable delay the slave will then transmit a return pulse back to the master. At the master, the elapsed time between the initial transmission and the receipt of the answering pulse is measured with a 60 megahertz clock. This time is corrected for the turn-around-delay inserted by the slave and scaled in distance units using the propagation speed of electromagnetic radiation.

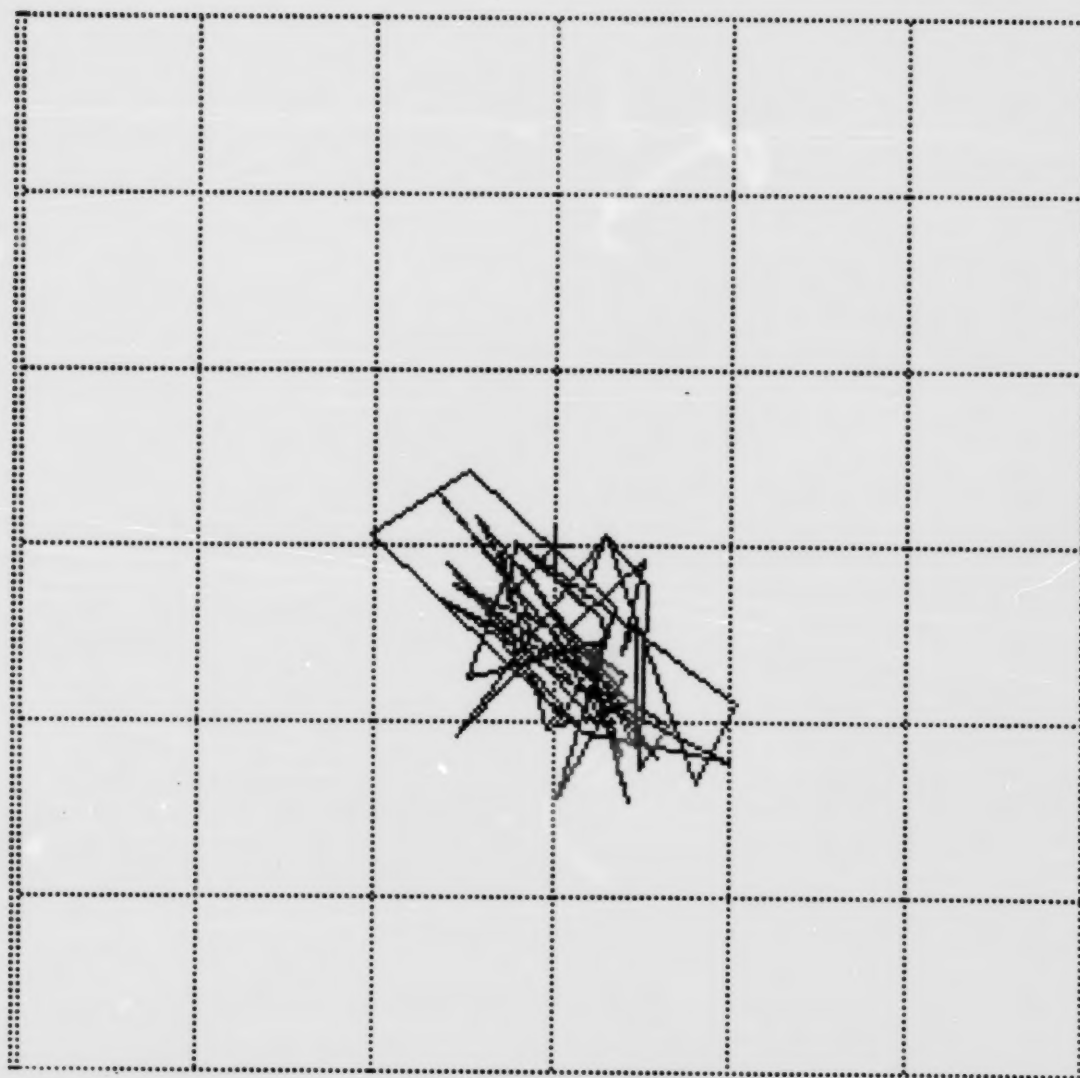
The control unit for this system was programmed to measure the range to each of the shore-based units once per second and transmit the ranges in digital format to the data acquisition computer HP9816 via the computer's RS-232C serial data port.

Prior to the Antarctic deployment the calibration constants for the radio positioning system were determined by the supplier. This was done by measuring the output range for each pair of transponders over a known calibration distance that had been surveyed to within the resolution of the instrument. Figure 2.2 provides an indication of the ranging system's overall positioning stability. The vertices of the random path shown in this plot represent successive positions computed from ranging data obtained while the ship was hove-to in the ice. Since the stability of each range is approximately constant at about ± 0.5 m, it can be considered adequate for the purpose of fixing the vessel's position during manoeuvre. The positioning stability shown here would be typical for all areas in which the manoeuvring tests were carried out.

The shore based stations were deployed by helicopter, one on the rim of a volcanic crater above McMurdo station, at a location known as Arrival Heights, and the other near a similar benchmark on Tent Island in McMurdo Sound near the ice edge. The locations of these two base stations are shown in the map of Figure 1.1. The distance between the two base stations were measured, using the positioning system itself, as 17706.5 metres. This agreed with the distance scaled from the charts of the area to within the accuracy with which the charts could be read. From these charts the bearing of the Tent Island site from the Arrival Heights location was determined to be 337.5 degrees true. The elevation of the Arrival Heights station was just under 200 metres from sea level and that at Tent Island was 137 metres, providing excellent line-of-site coverage over almost the entire ice covered extent of McMurdo Sound.

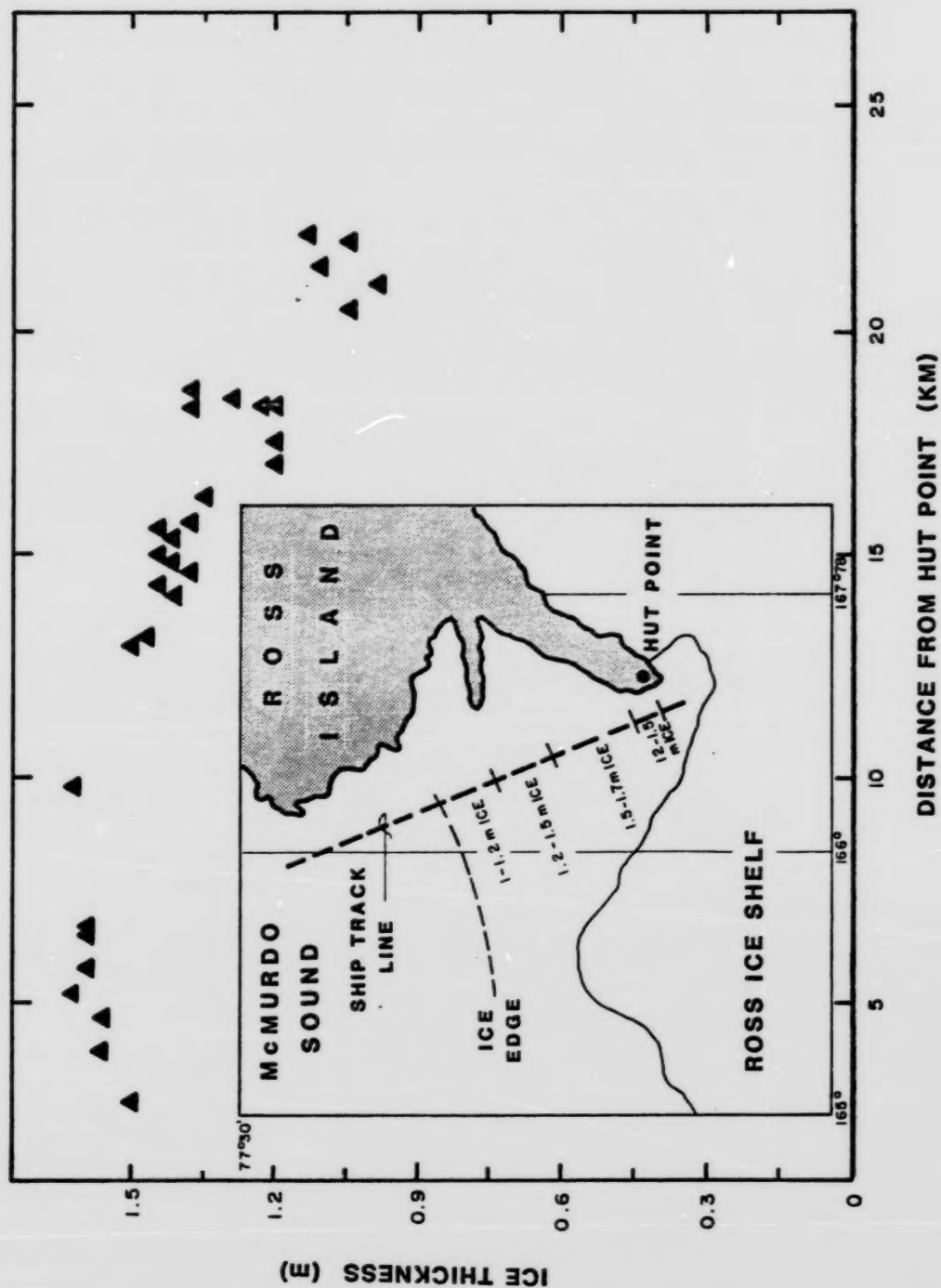
The two shore based transponders were deployed on the 20th of January with sufficient battery capacity at each site to permit a minimum of 100 hours of operation at zero degrees centigrade ambient temperature. Both units were still operating normally when recovered late on the 23rd.

FIGURE 2.2
STABILITY OF MICROWAVE POSITIONING SYSTEM



GRID SPACING: 1 metre

Figure 2.3 AVERAGE ICE THICKNESS from ICE EDGE to HUT POINT



Ice temperature profiles were measured at 7.5 cm intervals in each of the 21 cores taken during the test period. Most recorded temperatures were above -2°C . The warm core temperatures were the possible result of rotten, porous ice layers near the surface, allowing sea-water immersion of the cores. Salinities were obtained by measuring the conductivity of melt water from ice samples collected at 15 cm intervals in each core. Salinities near the surface were 0.5 to 6.0 ppt. Higher salinities of 6 - 8 ppt were measured from the water line to mid-core depth. The bottom portion of the core gave 4 - 6 ppt. The upper layer of ice for many cores appeared to be white crystalline and porous. This and the quick transition from low to high salinity just below the waterline suggested brine drainage through porous ice.

Based on the temperature and salinity recorded, ice flexural strength was estimated from Vaudrey's formulation for cantilever beam strengths. The mean flexural strength from the 21 ice cores collected was 180 kPa, based on a 100% core length. The minimum strength of 127 kPa occurred around the ice edge and Hut Point. The maximum strength of 228 kPa was associated with the thicker ice.

2.4 Data Acquisition System Software

The data acquisition system computer was equipped with 1.3 megabytes of central memory, providing space for its operating system, the data acquisition control program and buffering for up to 6900 seconds worth of data. The core of the data acquisition program consisted of a loop in which the computer polled the serial port to which the radio positioning system was connected for input data. This data was presented as a serial word, containing two ranges, once each second.

When the ranges were received the program then branched to a routine that triggered the analog-to-digital subsystem to scan all of the analog inputs and return their digital values to an input vector in the computer's memory. The routine would then read the system clock and store the time, together with the raw range, thrust and motion data in the data buffer. Finally, all of the measured parameters would be converted to engineering units, the ship's position would be calculated from the two ranges and a running plot of the ship's trajectory in the ice would be updated on the system CRT display along with a table giving the current thrust, speed, heading and rudder angle.

At this point program control would return to the loop polling the serial interface to await the next range transmission from the radio positioning system. From receipt of the serial range data this sequence required approximately 200 milliseconds to execute.

At the end of a test, which usually lasted from 1000 to 2000 seconds, the data buffered in the computer's memory would be written out to a micro-floppy disk volume to create a permanent machine readable record of the time series of data points for all parameters.

Additional software utilities were available to read the data back from disk and re-plot it at various scales. Interactive graphics tools were provided to allow the user to select portions of the ship's trajectory to be analysed for average rate of turning, total change of heading, elapsed time, distance run, average thrust, speed and rudder angle, and effective turning radius. For any such selected portion of the track, a brief report would be printed, giving these calculated quantities. In addition hardcopy of the plot of the ship's trajectory, showing the portion that had been selected for analysis, could also be obtained.

2.5 Video Documentation

Attempts to use a stationary camera or video was made to record ship position, but this did not provide any practical information. In order to provide visual documentation of the contact between the sides of the ship and the ice, two video recording systems were used. It was hoped that by making video imagery of the ice contact along both sides of the ship during various turning manoeuvres it would be possible to gain an understanding of how the ice forces acting along the hull affect turning and to obtain some idea of where those forces might be acting.

The video systems used were both colour VHS portable systems suitable for use in the strong daylight conditions prevailing during these tests. Both units were equipped with zoom lenses. They were operated by two members of the test team, each generally providing coverage of one side of the vessel.

Footage was shot from a number of locations along the main deck and on the flying bridge, this latter location providing the greatest fore-aft view of the hull-ice contact generally available from onboard the ship. On the ship's port side footage was also shot from the oceanographic platform which extends somewhat more than a metre outboard of the maindeck rail just aft of mid-ships and which affords a good view of the hull ice contact zone aft of this point.

It had also been planned that for some of the turning tests video would be shot from a helicopter to provide better coverage of the areas around the bows which are virtually impossible to see from onboard the vessel and to show the situation of the ship within its track from directly above. Unfortunately it was not possible to arrange the use of a helicopter at the times when the ship was engaged in the turning tests.

3. MANOEUVRING TEST PROGRAM

3.1 Ice Properties and Other Environmental Parameters

Ice cover in McMurdo Sound in January 1985 consisted of undisturbed landfast level sheets located at almost the same area near Hut Point as in January 1984. It extended over roughly 13 miles with very little snow cover. Average ice thickness in the manoeuvring area are shown in the inset in Figure 2.3. Ice thickness measurements were made and ice cores were extracted along the ship track from the ice edge to Hut Point. A total of 113 measurements were made and averaged to yield 36 separate data points. These were plotted and the results shown in Figure 2.3. The range of ice thicknesses was approximately 1 to 1.7 m with a 8 km stretch of thicknesses averaging about 1.6 m, .1 m. The ice was, therefore, of suitable uniform thickness for the desired testing. The availability of 24 hours of daylight, low winds, and moderate temperatures aided the ice profiling effort.

The manoeuvring tests of the POLAR STAR were conducted as a series of "S" turns, that is arcs or sectors of about 180 degrees executed back to back. Throughout each such arc the pitch order and rudder angle were held constant at the desired level until the required change in heading had been obtained. The test arcs were limited to about 180 degrees in order to avoid the anomalous results that can be obtained when the ship begins to approach its own track causing splitting and breakup of the ice pan left in the centre of the turn.

The major, independent sets of turning manoeuvres were conducted by the USCGC POLAR STAR during this deployment. The first set comprised three contiguous arcs and were carried out at the seaward edge of the land fast ice just west of the broken channel that was being prepared for the re-supply of McMurdo Station. These tests were commenced at 1100 hours on January 21, and required just over 30 minutes to complete. The second set of manoeuvres was conducted beginning at 1215 hours on January 22 and required one hour and fifty minutes to complete. These tests consisted of two sets of four arcs each and were also conducted near the seaward edge of the landfast ice, this time to the east of the McMurdo re-supply channel. The third set of manoeuvres was conducted beginning at 0150 hours on January 23 and required one hour and forty minutes. AS with the previous day's tests, this set also consisted of two groups of four arcs. These tests were conducted in the ice just to the east of the McMurdo re-supply track at a point about 2/3 of the way from McMurdo to the seaward edge of the land fast ice.

During these tests the POLAR STAR was at a relatively light draft, having onboard only some 360,000 gallons of fuel oil. The ship's ballast condition is summarized in Table 3.1.

Throughout these tests the steering system appeared to be in good working order and functioned normally at all times. Keeping a steady course generally presented no difficulty in ice, although the actual rudder angle seemed to deviate appreciably from the ordered helm, indicating that controllability is influenced by ice thickness variations.

TABLE 3.1

LOADING CONDITION OF USCGC POLAR STAR DURING ANTARCTIC
MANOEUVRING TESTS, JANUARY 1985

Draft Forward	25.0 feet (7.62 m)
Draft Aft	27.0 feet (8.22 m)
Waterline Length (at these drafts)	337.5 feet (102.87 m)
Max. Beam at Waterline	76.0 feet (23.16 m)
Design Draft	28.0 feet (8.53 m)
Design Waterline Length	352.0 feet (107.29 m)

TABLE 3.2

TEST MATRIX OF STARBOARD TURNS

ICE THICKNESS (ft) (m)		HELM ORDER			
		10°	15°	20°	25°
6	1.8	-	-	1/2	-
5	1.5	-	-	1/2 1/2 1/2	-
4	1.4	1/3	-	1/3	-
3	0.9	-	-	1/3	1/3 1/3 1/3
2	0.6	-	-	-	-
1	0.3	-	-	-	-

1/3 = one arc at 18,000 HP

1/2 = one arc at 32,000 HP

TABLE 3.3

TEST MATRIX OF PORT TURNS

ICE THICKNESS (ft) (m)		HELM ORDER			
		10°	15°	20°	25°
6	1.8	-	-	-	-
5	1.5	1/2	1/2 1/2	1/2	-
4	1.2	-	-	1/3 1/3	1/3
3	0.9	-	1/3	1/3	-
2	0.6	-	-	-	-
1	0.3	-	-	-	-

1/3 = one arc at 18,000 HP

1/2 = one arc at 32,000 HP

Difficulty was experienced, however, in obtaining and maintaining desired pitch settings on both of the wing propellers. Despite ordering equal pitch settings, these two shafts typically exhibited significantly different and highly variable thrust, with the starboard propeller usually developing more thrust than the port one.

Tests 1 to 3 inclusive were done using 2 diesels to power each shaft for a nominal maximum output of 18,000 HP. Tests 4 and 5 were done with two diesels powering each wing shaft and a gas turbine powering the centre shaft for a total of 32,000 HP maximum.

The matrix of test points obtained in these tests is shown in Tables 3.2 and 3.3. The tables illustrate the test program by port and starboard turns. Note that the "1/3, 1/2" designation does not refer to the engine power level, but rather is an indication of the nominal available SHP.

4. DATA REDUCTION AND ANALYSIS

4.1 Overview of Reduced Data

The ten (10) channels of digital data described in Section 2.1 were recorded in specially labelled files on five (5) single disk volumes for easy access. The data are stored in such a manner that time series analysis of any particular channel can be carried out if desired. The onboard data acquisition system provided real-time data reduction and near real-time data analysis capabilities. The ship's course was plotted in real time onboard for quick assessment of the data quality. The digitized "raw" data were stored on diskettes in readily accessible format for future use. All the turn trajectories have been re-plotted after smoothing and scaling and are attached as Appendix D. For each "steady" arc of the turning circle, the mean values of thrust in each shaft, the total thrust, ship speed and rudder angle were computed along with an estimate of the turning radius, the mean rate of change in heading and the time taken to turn 180° . A total of 19 distinct data points were recorded during the three sets of manoeuvres conducted. Data for each sector (or arc) were used to obtain the kinematic variables given in Table 4.1. Since the data covered only a limited range of rudder angles and ice thickness, only a general trend could be deduced. It appears that the steady rate of turn in ice decreases with increasing ice thickness and the time for a given heading change increases with ice thickness.

TABLE 4.1

SUMMARY OF KINEMATIC VARIABLES FROM STEADY TURNS

TEST/ SECTOR	DIRECTION OF TURN	ORDERED HELM (deg.)	LENGTH OF COURSE (m)	ELAPSED TIME (minutes)	CHANGE IN HEADING (deg.)	AVERAGE SPEED (kt)
1/1	S	10.0	250.1	1.5	5.9	5.4
1/2	S	20.0	1337.3	8.8	116.1	4.9
1/3	P	20.0	367.3	2.6	48.9	4.5
2/1	S	20.0	1255.4	7.6	83.2	5.3
2/2	P	20.0	998.0	7.9	149.9	4.1
2/3	S	25.0	2319.2	17.1	178.8	4.4
2/4	P	25.0	1013.2	9.3	176.8	3.5
3/1	P	20.0	625.3	4.7	84.3	4.4
3/2	S	25.0	872.5	6.6	59.9	4.3
3/3	P	15.0	1637.7	11.2	173.3	4.7
3/4	S	25.0	1375.6	9.0	89.2	5.0
4/1	S	20.0	848.5	7.2	87.9	3.8
4/2	P	15.0	998.3	9.5	159.6	3.4
4/3	S	20.0	821.7	6.5	106.0	4.1
4/4	P	15.0	569.5	5.5	80.9	3.4
5/1	P	20.0	604.3	4.0	91.4	4.9
5/2	S	20.0	402.3	2.9	42.3	4.5
5/3	P	15.0	984.4	6.6	133.0	4.8
5/4	S	20.0	374.3	2.8	47.8	4.4

4.2 Analysis of Manoeuvring Data

A review of the test data is given in Table 4.2, which shows the following items:

- Test/sector number of the trial
- Ordered helm
- Actual helm
- Direction of turn (Port or Starboard)
- Average speed in turn, V
- Average ice thickness, h_i
- Total shaft thrust T_{total}
- Thrust distribution over port, centre and starboard shaft as a percentage of the thrust (P, C, S)
- Turning radius to length ratio, R/L

In general, the manoeuvring performance of the POLAR STAR indicated that the turning radius depends on the rudder angle, the ice thickness and the power level. These dependencies have been illustrated in detail in graphical form and are included in Appendix A, along with the open-water turning data available for the vessel. Here, we have focussed on the turning performance of the vessel in the light of the actual test conditions that existed during the trials. For a triple screw ship, the propeller thrust distribution also has a significant influence on the turning characteristics of the vessel. When reviewing the present test data, it was noticed that the thrust affected the turning ability of the vessel in two ways:

- (a) The thrust level at the centre propeller that generates a propeller induced flow over the rudder, made the rudder more effective at higher thrust. This was proven in the rudder hydrodynamics model developed in [2] and discussed in Section 5.2.
- (b) The imbalance in the thrust distribution, between the three shafts assisted the ship to turn better in one direction. For example, a higher thrust at the starboard propeller results in a smaller turning radius to port than to starboard.
- (c) The effect of the centre propeller rotation also helps the ship to turn better to port than to starboard.

The test data can be categorized in groups as follows:

- The ship speed can be considered to be in the range of 2.2m/sec to 2.3m/sec for all tests. As in the open water turning performance, ship speed has little influence on the turning characteristics, within the range of speeds tested. Therefore speed is assumed as an independent parameter for the present test data.
- There are basically three groups of ice thicknesses which can be represented by:

$$\begin{aligned}h_i &= 1.12 \text{ for test 1} \\h_i &= 0.93 \text{ for tests 2 and 3} \\h_i &= 1.49 \text{ for tests 4 and 5}\end{aligned}$$

TABLE 4.2
REVIEW OF TEST DATA

TEST SECTOR	RUDDER		P/S TURN	V m/sec	h _i m	T _{total} kN	PROP. THRUST %			R/L
	ORDERED DEG.	ACTUAL DEG.					P	C	S	
1/1	10.0	10.3	S	2.8	1.12	924	39	26	36	23.8
1/2	20.0	20.0	S	2.5	1.12	1106	24	39	37	6.4
1/3	20.1	19.0	P	2.3	1.12	1198	35	43	22	4.2
2/1	20.0	17.1	S	2.7	0.84	929	4	60	36	8.4
2/2	20.0	20.0	P	2.1	0.93	898	16	55	29	3.7
2/3	25.0	21.8	S	2.3	0.93	1023	8	55	37	7.2
2/4	25.0	25.8	P	1.8	1.02	1010	18	50	31	3.2
3/1	20.0	21.4	P	2.3	1.02	831	23	42	34	4.1
3/2	25.0	23.4	S	2.2	0.93	836	14	36	50	8.1
3/3	15.0	17.3	P	2.4	0.93	823	23	35	42	5.3
3/4	25.0	21.9	S	2.6	0.84	790	11	38	52	8.6
4/1	20.0	21.7	S	2.0	1.63	1506	3	84	13	5.4
4/2	15.0	15.1	P	1.7	1.49	1216	9	96	6	3.5
4/3	20.0	22.4	S	2.1	1.49	1438	2	89	9	4.3
4/4	15.0	10.6	P	1.7	1.35	1175	11	88	1	3.9
5/1	20.0	19.3	P	2.5	1.35	1214	8	91	0	3.7
5/2	20.0	19.0	S	2.3	1.49	1446	3	86	11	5.3
5/3	15.0	13.6	P	2.5	1.49	1221	6	93	0	4.1
5/4	20.0	18.3	S	2.3	1.63	1454	3	88	10	4.4

- the mean thrust distribution over the port, centre and starboard shafts as a percentage of the total thrust are:

30/40/30 for test 1
 12/55/33 for test 2
 18/38/45 for test 3
 5/90/5 for tests 4 and 5.

- The following four groups of data can be identified:

Group	Tests	Ice Thickness	Thrust Distribution
A	1/2, 1/3	1.12 m	30/40/30
B	2/1, 2/4	0.93 m	12/55/33
C	3/1, 3/4	0.93 m	18/38/45
D	4/1, 5/4	1.49 m	5/90/5

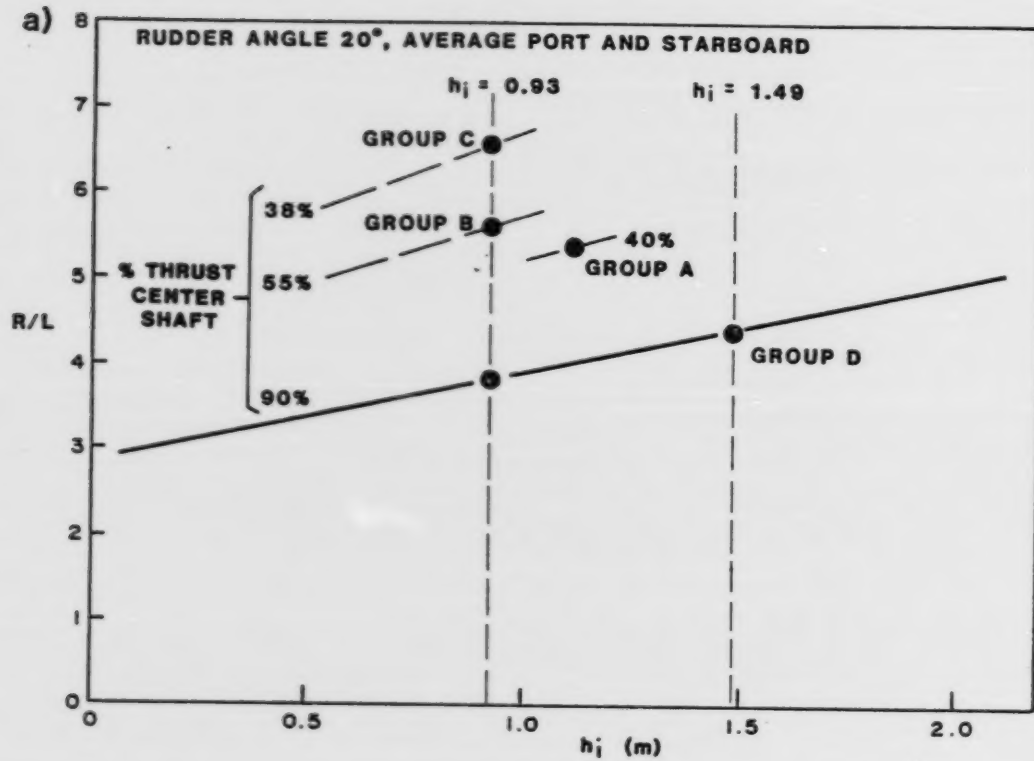
In grouping the data as above the test 1/1 has been excluded from consideration as it is a single test carried out at a rudder angle of 10° and is associated with an unusually large turning radius ($R/L = 24$). Further, this test is associated with the lowest center-shaft thrust and is a turn to starboard which has consistently produced large turning radius. All the above factors point to the need for additional data points under the same conditions of ice thickness and rudder angle.

From reviewing all the other data the following trends were noticed:

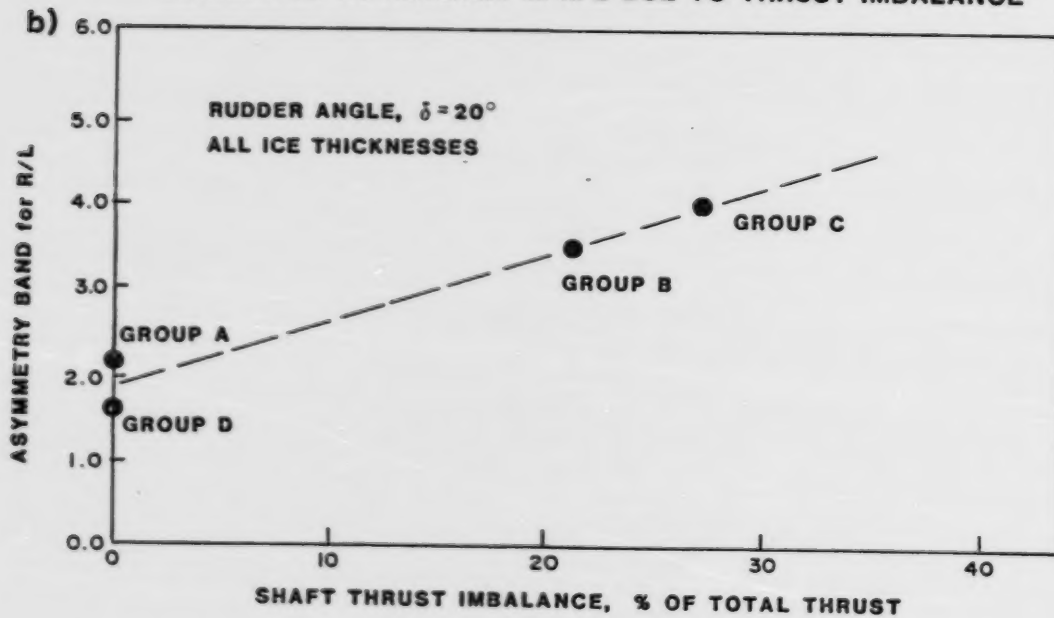
- The turning radius for port turns is smaller than for starboard turns, even when the thrust distribution is balanced. Compare tests 1/2 and 1/3 and tests 5/1 and 5/2 where the difference in R/L is 1.6 to 2.2.
- Higher loading on the center propeller produces a smaller turning radius. Compare tests 2/2 and 3/1 and tests 2/3 and 3/4.
- As noticed before, the speeds have been maintained fairly constant throughout the trials. In thicker ice, however, a higher thrust was required, which in turn increased the rudder effectiveness. Furthermore, the center propeller developed 90% of the thrust in Group D. Therefore, the radius to length ratios were rather low in these tests. When extrapolating the average R/L of Groups C (38% center shaft thrust) and B (55% center shaft thrust) to the same thrust distribution as Group D with 90% thrust on the center shaft, see Figure 4.1a, the trend of Figure 4.1a was obtained for a rudder angle of 20 degrees. Plotting the average R/L of Group A with 40% thrust at the center shaft, it is clear that this test was conducted in rather weak ice.

FIGURE 4.1

VARIATION of R/L WITH ICE THICKNESS



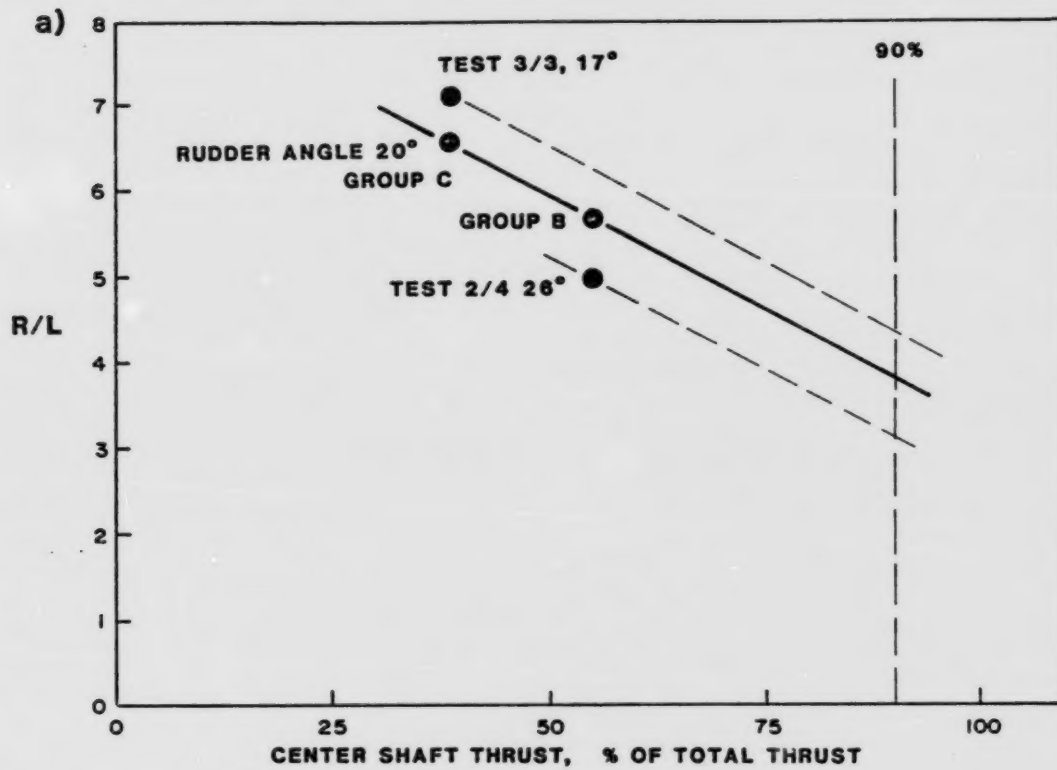
ESTIMATED ASYMMETRY in R/L DUE TO THRUST IMBALANCE



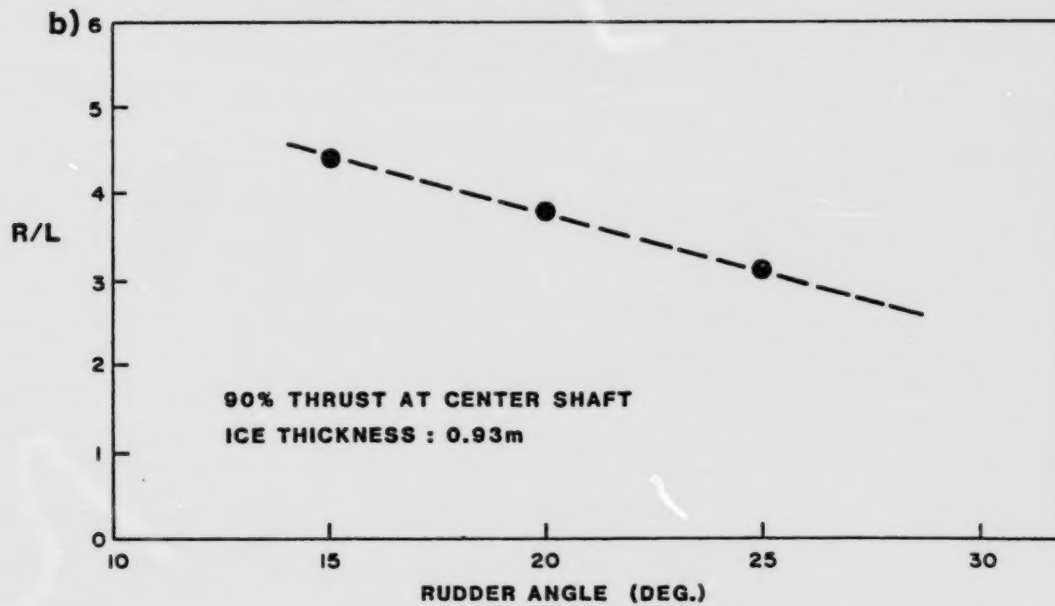
- The thrust level of the outboard shaft (e.g. starboard shaft in port turn) reduces in the turn compared to its straight ahead value. The thrust level of the inboard shaft increases. The distributions of thrust over the three shafts given above have been estimated from various combinations of tests. In each of the groups that have been identified, it can be seen that the thrust levels of the port and starboard shafts fluctuate around a mean value, which is assumed to be the nominal thrust level in the straight ahead condition.
- The turning tests at 15 degrees rudder angle in Group D show rather low values of R/L compared to the values for the 20 degree rudder angle. All these turns to port, in general, produced lower R/L values. The average R/L for 15 degrees rudder angle to port is 3.83. If we define the band of asymmetry as the absolute value of the difference between the R/L port and starboard, then adding half the asymmetry band to $R/L = 3.83$ will give a value of $R/L = 4.63$. The average R/L for 20 degrees helm is 4.35. The magnitude of the asymmetry band and the imbalance in the thrust distribution have been estimated and are plotted in Figure 4.2.
- The standard deviation between the ordered and actual measured helm is about 2.0 degrees. Three of the four ordered 25 degrees helm result in lower actual helm. When test 2/4 is considered, 26 degrees helm, the port turn R/L of 3.2 would give the bandwidth of Figure 4.2, an average port and starboard turn R/L of 4.95, which with Figure 4.2 extrapolated to 90% center shaft thrust would give a value for R/L of 3.1. Similarly, for test 3/3, a value for R/L of 4.4 is obtained for a rudder angle of 17 degrees. The results are plotted in Figure 4.2a.

FIGURE 4.2

VARIATION of R/L WITH CENTER SHAFT THRUST



VARIATION of R/L WITH RUDDER ANGLE



4.3 Conclusions for the Analysis of the Full-Scale Test Results

From the above analysis, a number of conclusions have been arrived at. These are discussed below:

- i) In addition to the standard variables such as rudder angle, ice thickness and ship speed, the propeller thrust has a significant influence on the manoeuvring capabilities of the POLAR STAR.
- ii) The effect of propeller thrust on steady turning can be divided into three categories: total thrust which governs the straight-ahead icebreaking and hence the turning capabilities, the distribution of the thrust between the three shafts which determines the rudder effectiveness and thirdly the thrust imbalance between the three shafts which introduces asymmetry in the port and starboard turns.
- iii) Based on the data analyzed and the factors described above, it can be shown that for a given total thrust the difference between the R/L port and starboard can be as high as 100%.
- iv) It seems that the most effective manoeuvring method will involve developing 90% of the total thrust on the center shaft and turning to port whenever possible.

5. TIME DOMAIN MANOEUVRING SIMULATION

5.1 Background

As part of the requirement of the project, a manoeuvring performance predictor was developed to be used and evaluated in conjunction with the full scale test program. The numerical model is based on conventional manoeuvring equations with coefficients extracted from model test data.

5.2 Basic Assumptions and Available Data

The diameter of the circular path of steady turning of a vessel is the most direct measure of its manoeuvrability. The smaller the turning diameter, the more manoeuvrable the vessel is said to be. The three dynamic modes which constitute the steady turning motion in level unbroken ice are surge, sway and yaw. The other three modes, heave, pitch and roll become important when unsteady motions in non-uniform ice are considered such as ramming a ridge. These cases are not treated in the present mathematical model. One method that is amenable to calculation of the three horizontal modes of motion utilize the principles of rigid body dynamics and functional representations of external forces. Such a method is used in the development of the mathematical model that allows computation of the turning trajectory as a time-stepping process. The advantage of the present method is that it is amenable to any other kind of unsteady vessel manoeuvres such as captain's manoeuvre (back and fill turn). The mathematical details of the nonlinear equations of motion are given in Appendix B.1. The main assumptions used in the development of the model are given below:

- i) The medium in which the vessel operates has uniform physical and mechanical properties, ie. the ice is of uniform thickness and strength.
- ii) Turning forces on the hull are expressible as linear combinations of terms involving first power velocities and accelerations. This is obtained by Taylor series expansion of the forcing functions and neglecting higher order terms. (Details in Appendix B.).
- iii) The hull derivations (coefficients of the hull force terms) can be determined from controlled scale model tests.
- iv) Longitudinal forces on the hull can be represented by empirical formulations of level straight-ahead icebreaking resistance and propeller thrust.
- v) Rudder-induced forces on the hull can be computed separately using empirical formulations of lift, drag and propeller slip-stream effects.
- vi) Forces on the hull from propellers and rudders are not affected by ice interaction.
- vii) Hydrodynamic effects associated with acceleration only, are accounted for. Shallow and restricted water effects as well as square-law drag forces due to current are negligible in comparison to the ice forces.

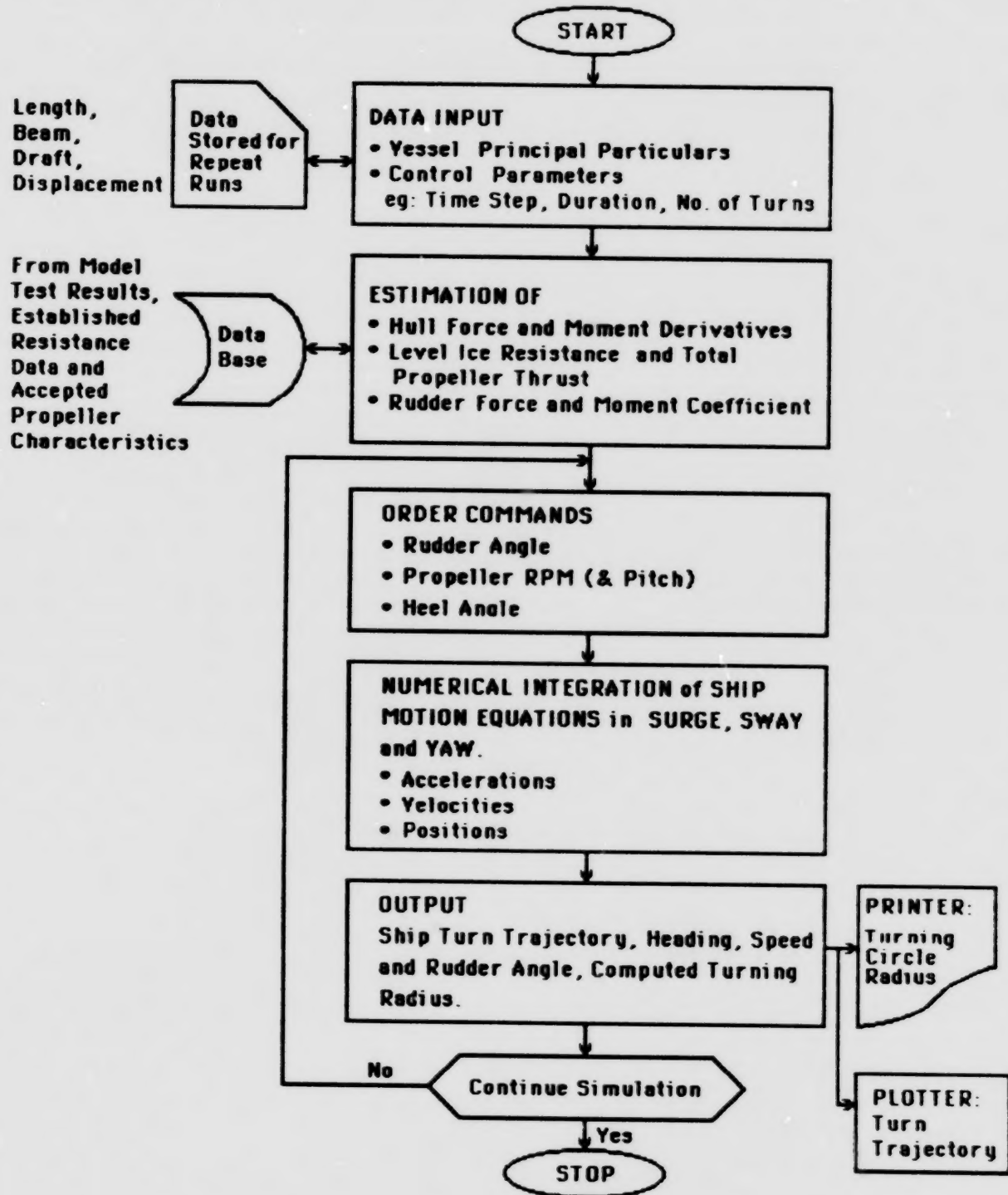
5.3 Outline of Numerical Model

The outline of the time-domain simulation model for manoeuvring in level ice is shown in Figure 5.1. It is a Level I flow diagram of the computer program depicting the three main stages in the algorithm: the initialization stage, the computation stage and the output stage. By inputting the minimum necessary data such as the principal particulars of the vessel, propeller and rudder, the time-stepping calculations can be initiated. The hull derivatives (the hydrodynamic coefficients and ice-force coefficients) are estimated using the semi-empirical data stored in the code. The computations can be initiated at the keyboard by typing in the throttle setting and the helm order. In the calculation stage, the ship positions are computed by numerically integrating the equations of motion using the initial conditions specified in Stage 1.

The equations of ship manoeuvring dynamics detailed in Appendix B.1, are derived from the theory of ship motions as well as approximate formulations of rudder and propulsion dynamics. The external forces on the hull are expressed in the form of linear functions of velocities and accelerations in the sway and yaw modes. The thrust and resistance characteristics of USCGC POLAR STAR have been extracted from data acquired during previous full-scale tests. The manoeuvring equations are sufficiently general in character and are applicable to conventional icebreaking hull forms. The hull force coefficients were obtained from [4], wherein non-dimensional parametric model test data on typical icebreaking hull forms are given. The rudder forces have been determined using an existing sub-program given the rudder geometry, ship speed or power level, propeller slip-stream characteristics and hydrodynamic data on low aspect ratio control surfaces.

The computation of rudder forces involve calculating the flow velocity over the rudder, and then calculating the lift using the tabulated values of the lift coefficient for angles of attack up to the stall angle. The effective angle of attack for relative flow at the rudder accounts for drift angle at the rudder brought about by the turning of the ship. The angle of attack equals the rudder angle for the case of zero ship speed when the propeller induces a local flow over the rudder, and also in the initial stages of a manoeuvre when the rudder is first moved and the ship has not yet responded. The flow velocity is related to the mean squared velocity (U_R^2). This in turn is determined from the induced mean axial velocity at the point of interest on the rudder. Evaluation of this requires information on the open water characteristics of the propeller, propeller diameter and location, propeller RPM, rudder geometry, and the ship forward speed. Computation of the lift takes into account the effective rudder area, which is the actual rudder area multiplied by several factors. These factors are the area correction, hull-rudder interference correction and the effective aspect ratio correction.

FIGURE 5.1
SCHEMATIC OF TIME-DOMAIN MODEL

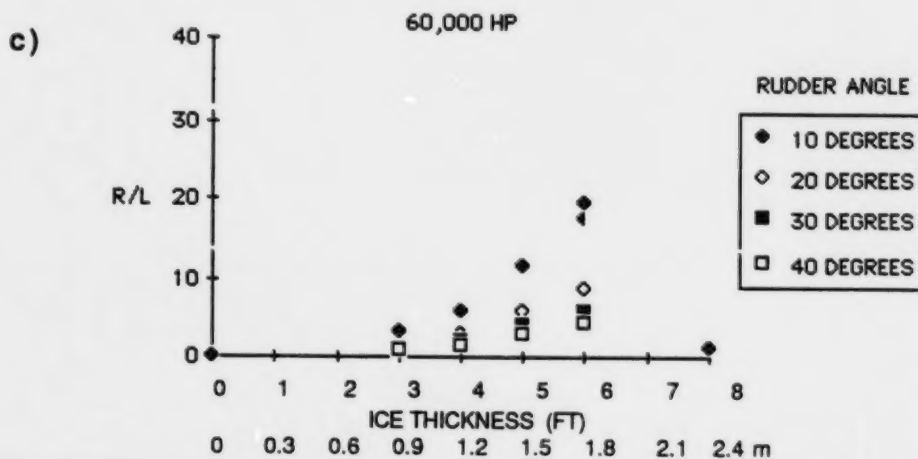
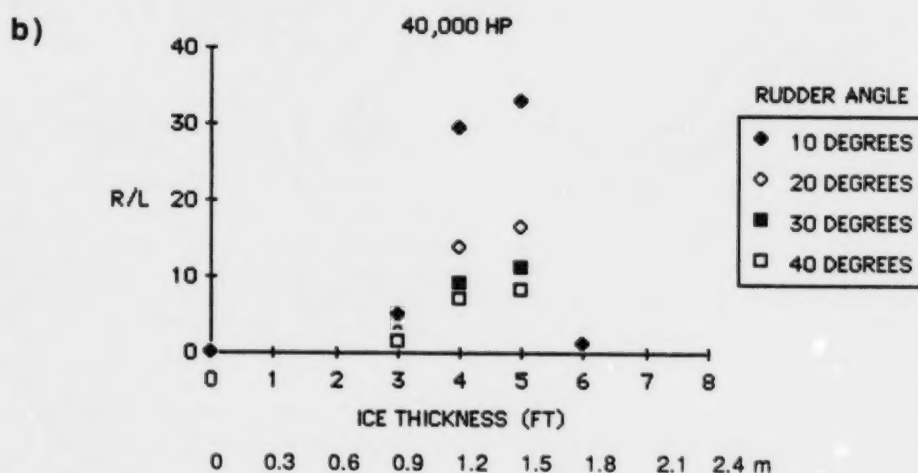
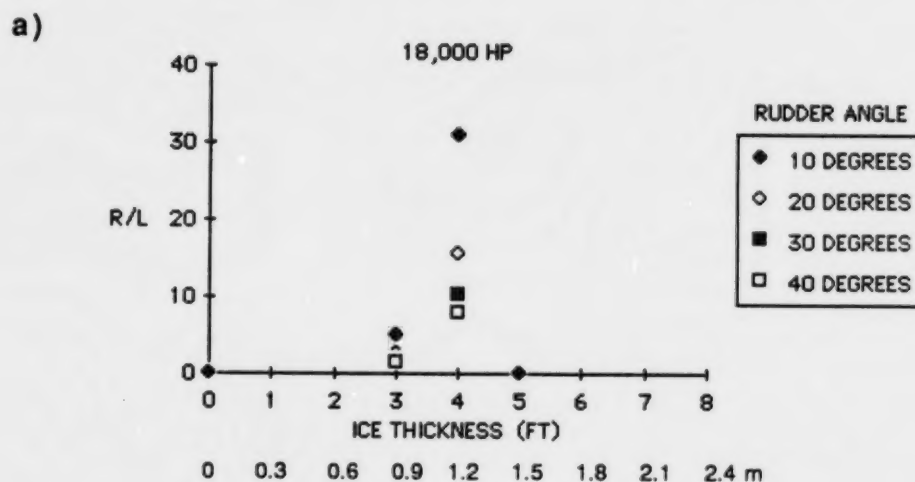


5.4 Predictions for USCGC POLAR STAR

To conform to the contract requirements, the numerical model was readied for use onboard the vessel. However, limitations of equipment weight on the air transport to McMurdo Sound prevented the use of a second computer for model execution. Therefore, prior to departure the model was run extensively to cover all possible ranges of parameters such as ice thickness, ship speed, power level and rudder angle and prediction curves developed. Preliminary comparisons of the predicted and measured turning circle radii were made onboard the vessel on an opportunity basis.

The variation of the ship turning radius with ice thickness for rudder angles from 10 to 40 degrees at 18,000, 40,000 and 60,000 horsepower are shown in Figures 5.2 (a), (b) and (c). An ice thickness range of .9 to 1.8 m was chosen for making the computations, as this essentially represents the continuous mode operating range of the vessel. Furthermore, this represents the range in which model test data on the linear hull derivatives are available. However, it can be seen from the figures that predictions were obtained in the entire range of .9 to 1.8 m only for 60,000 HP. At 40,000 as well as 18,000 HP, the model failed to give steady turning radii in 1.5 and 1.8 m of ice respectively. Examination of the computations into the initial turning phase indicated that the ship speed in the turn at these ice thicknesses were computed as zero, thereby terminating further computations. The turning radius, which is shown non-dimensionalized by ship length (R/L) increases with ice thickness in all three cases. The effect of ice thickness is reduced as power is increased, shown by the slope of the radius-thickness curve. The power level clearly plays a dominant role in the predicted turning capability of the vessel. This is because at higher power levels the propellers are heavily loaded, which generates a higher flow velocity of the rudder, thereby making the rudder more effective. As might be expected, the effect of rudder angle diminishes as the angle increases. This can be seen in the "asymptotic" behaviour of R/L with rudder angle at any particular ice thickness.

Figure 5.2
COMPUTED TURNING RADIUS with ICE THICKNESS and RUDDER ANGLE



6. MATHEMATICAL MODEL OF STEADY TURNING IN UNBROKEN ICE

6.1 Overview of Model and Basic Assumptions

In this section, the development of a first predictive mathematical model of the steady turning performance of icebreakers with conventional* bow forms in level, unbroken, homogeneous ice fields is described. The model was developed by Canadian Marine Drilling Limited (Canmar), as subcontractors on the present POLAR class project. Canmar's extensive operational experience in the Beaufort Sea onboard the support/supply vessels KIGORIAK AND ROBERT LEMEUR provided the ideas for a simple hull-ice force balance method which forms the basis of the model. The main assumptions used in the development of the mathematical model are listed below:

1. The magnitudes of the hydrodynamic forces are small compared to those of the ice forces acting on the hull.
2. For conventional icebreaking hull forms, the bow geometry can be represented by a simple flat-plate wedge.
3. It is assumed that the midbody side force counteracting the centrifugal force can be represented by a point load on the outboard side of the ship, the location of which varies with ship design.
4. The total ice resistance in the straight-ahead mode is concentrated on the ship bow and acts in the opposite direction to the motion.
5. The net asymmetric ice forces on the bow in the transverse direction is proportional to the difference in the volume of ice broken by the bow per unit time.
6. The ship centre of rotation is at its centre of gravity.
7. In the steady state, the ship is assumed to turn about a fixed centre of the turning circle.

The methodology and the detailed derivation of the governing equations are given in Appendix C.

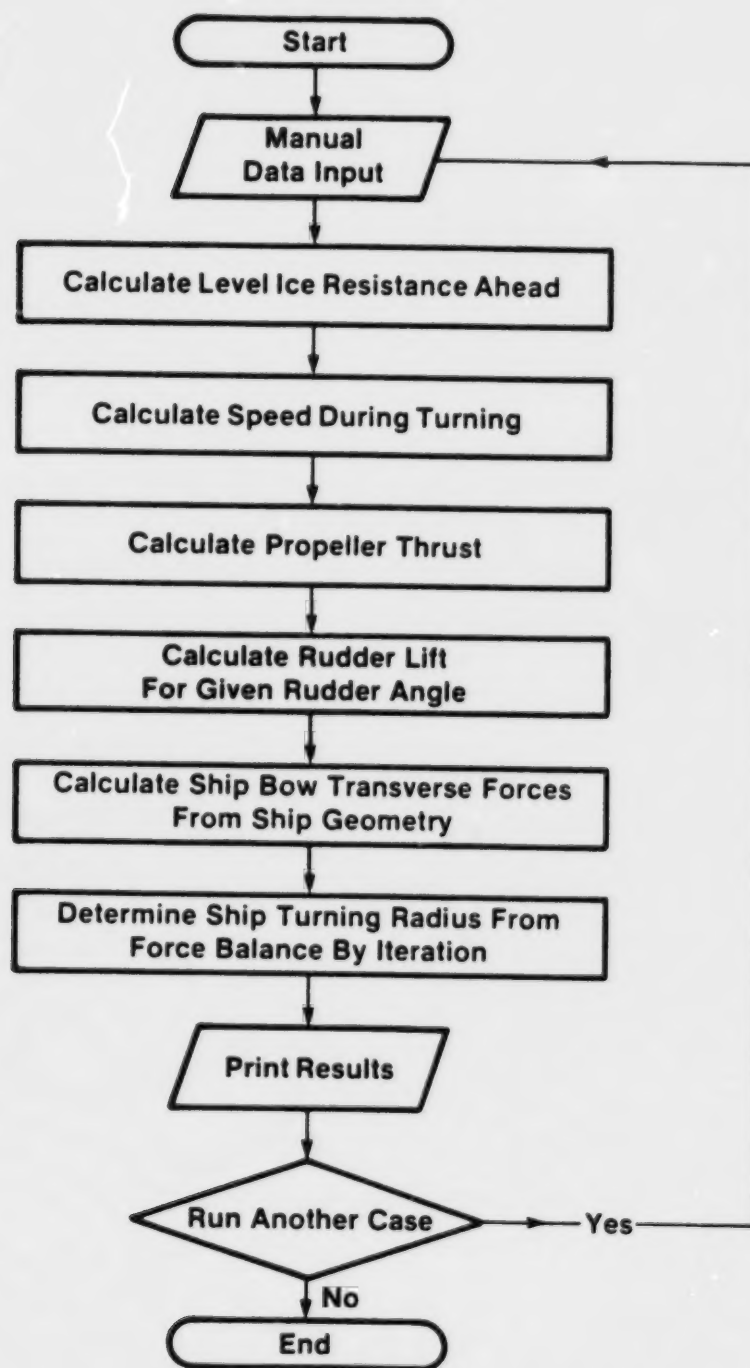
6.2 Computer Program

The computer program is conveniently set up as a series of subroutines which are only applicable to a particular ship or a class of ships. The flow chart in Figure 6.1 indicates that there are six main modules.

The program must be supplied with the input data which consists of the ship particulars, ship performance in ice and propeller and rudder particulars. These input data are declared as variables in the program.

*Spoon bows are not included in the present development.

FIGURE 6.1
**Mathematical Manoeuvring Model
Flow Chart**



The level ice resistance for a ship moving straight ahead in ice of specified thickness is then computed. The ship speed during the turn is estimated, from which the propeller thrust and rudder lift force are calculated.

Using the bow geometry, the next subroutine calculates the symmetrical transverse force acting on the bow when the ship is moving ahead. The force balance in the steady state turning phase is then calculated by an iterative process to determine the turning radius of the ship.

The first estimate of the turning radius assumes a zero friction case, which is improved subsequently by iterations to include frictional forces. The turning radius takes into account the rudder induced forces, bow forces and midship hull forces in equilibrium. The results are outputted to the printer. The computations can be repeated for other cases involving different rudder angles or ice thicknesses.

The user instructions for the computer program are included in Section 3 of Appendix C along with sample input session, outputs of all runs made and a listing of the source code.

6.3 Predicted Turning Radius

There are two variants of the mathematical model of steady turns in ice. The differences are primarily in the ice resistance formulations and rudder force calculations as indicated below:

1. For prediction for USCGC POLAR STAR:

a) $R_{ice} = 921 H^2 + 348 HV$

where R = ice resistance (kN)

H = ice thickness (m)

V = ship speed (m/s)

b) Hydrodynamic rudder lift calculations performed using Arctec's model RUHL [4].

2. For Canmar Model Prediction v/s Measurements

a) $R_{ice} = 512 H^2 + 107 HV$

b) The actual measured thrust from the centre wing port and wing starboard propellers were used.

c) Rudder lift calculated from ideal propeller theory.

During the turning process, the ice forces are randomly distributed on the outboard side of the ship. In order to facilitate computation of the ice forces, the distribution of the contact force was idealized. The following distributions of ice contact forces have been suggested based on full scale observations and operational experience.

- (1) Point load at the end of the parallel midbody or Ellipsoidal force distribution for ship with long effective parallel midbody, l_e (Figure 6.2 (a)).
- (2) Triangular or trapezoidal force distribution for short effective parallel midbody, l_e (Figure 6.2 (b)).

The contact force distribution used in the model will have to be calibrated from full scale and model tests data, in order to determine the relationship between effective parallel midbody and other parameters affecting the pressure distribution.

The mathematical manoeuvring model was run using the USCGC POLAR STAR particulars as input. The prediction of the ship resistance in level ice was based on normal winter ice conditions. The midbody side force was assumed to be distributed trapezoidally (2:1) over the effective parallel midbody of the ship. The predicted turning performance of the USCGC POLAR STAR in various ice thicknesses, power levels and rudder angles are given in Figures 6.3 to 6.5.

The results show that the model predicts correctly the expected trend of the turning radii in ice. Figures 6.3 to 6.5 show that the ship turning radii increase with increasing ice thickness. Also with greater power and at higher rudder angle, the ship turns within a smaller turning circle.

The predicted turning radii can only be approximate since they are dependent on the validity of the assumptions used and also on the accuracy of the other calculated parameters such as the rudder lift force. The effects on wake and propeller race on rudders in the icebreaking mode are rarely known with certainty. These uncertainties therefore affect the accuracy of the estimated rudder lift forces. It is suspected that the relatively small turning radii predicted in Figure 6.4 for the power level of 18,000 SHP have been affected by the rather high rudder lift force calculated in this case.

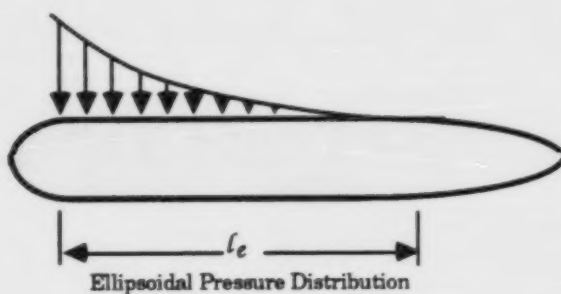
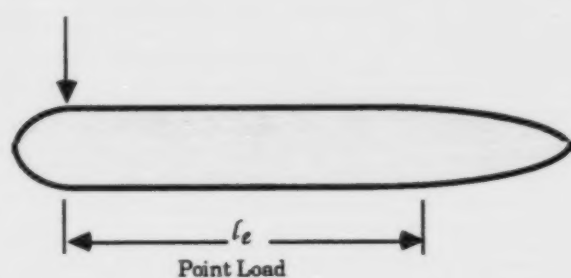
The changes in the location of the resultant midbody side force due to the variation in ship speed, ice thicknesses and rudder angles have not been accounted for in this model.

It is expected that in thicker ice and at lower ship speed, the predicted turning radius should be more accurate since the hydrodynamic forces are then relatively low compared to the ice forces.

FIGURE 6.2

TYPICAL HULL SIDE FORCE DISTRIBUTIONS MODELLED

(A)



(B)

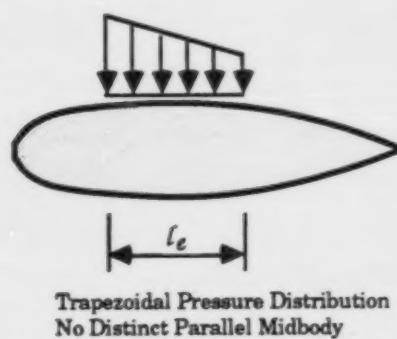
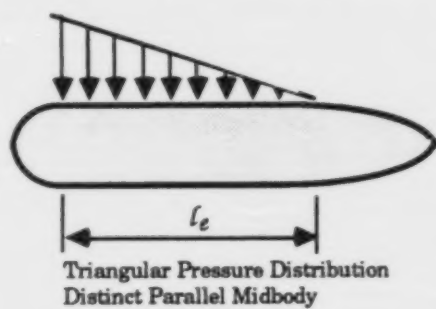


FIGURE 6.3

Polar Star: Predicted Turning Radius Per Unit LBP

Average Ice Flexural Strength : 300 Kpa

Power Level: 60000 SHP

Trapezoidal(2:1) Midbody Side Force Distribution

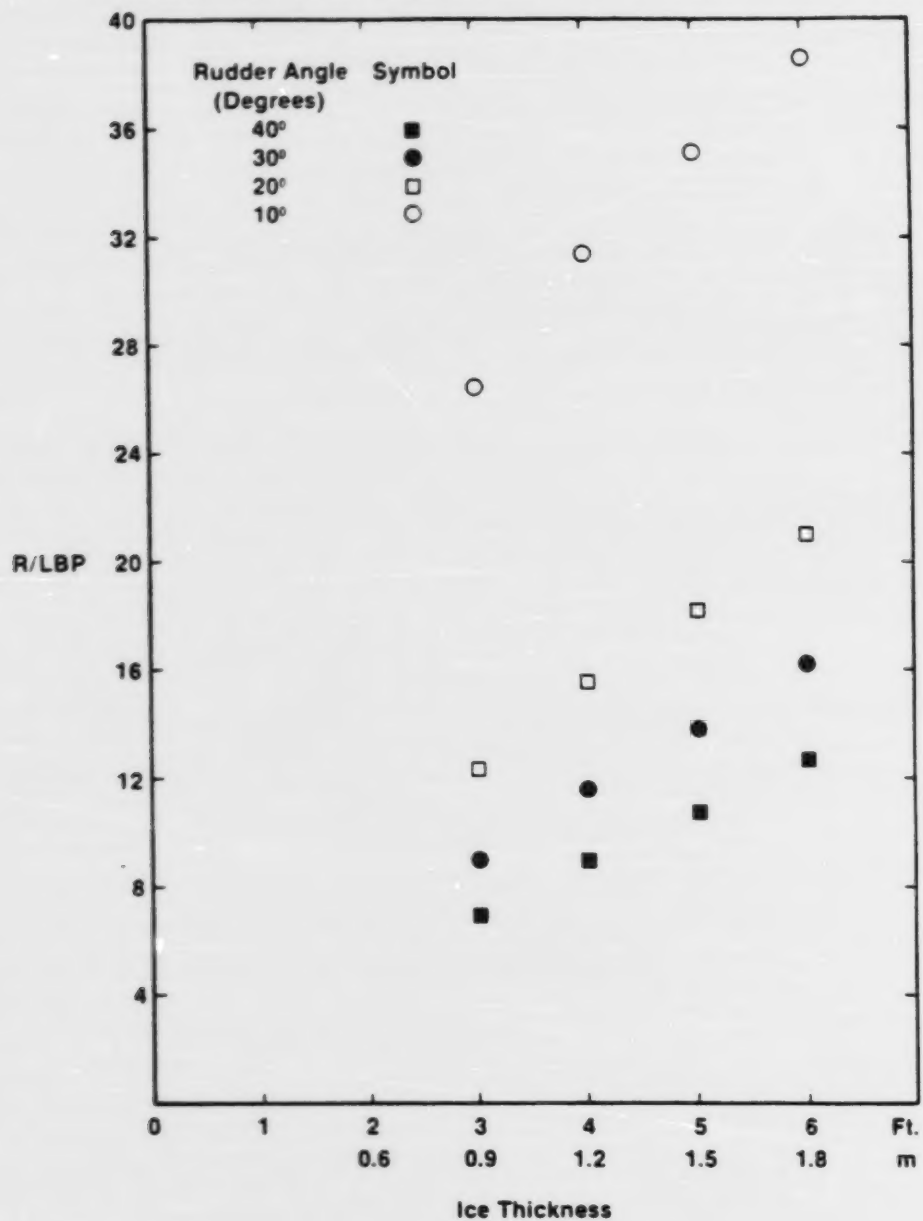


FIGURE 6.4

Polar Star: Predicted Turning Radius Per Unit LBP

Average Ice Flexural Strength : 300 Kpa

Power Level: 40000 SHP

Trapezoidal (2:1) Midbody Side Force Distribution

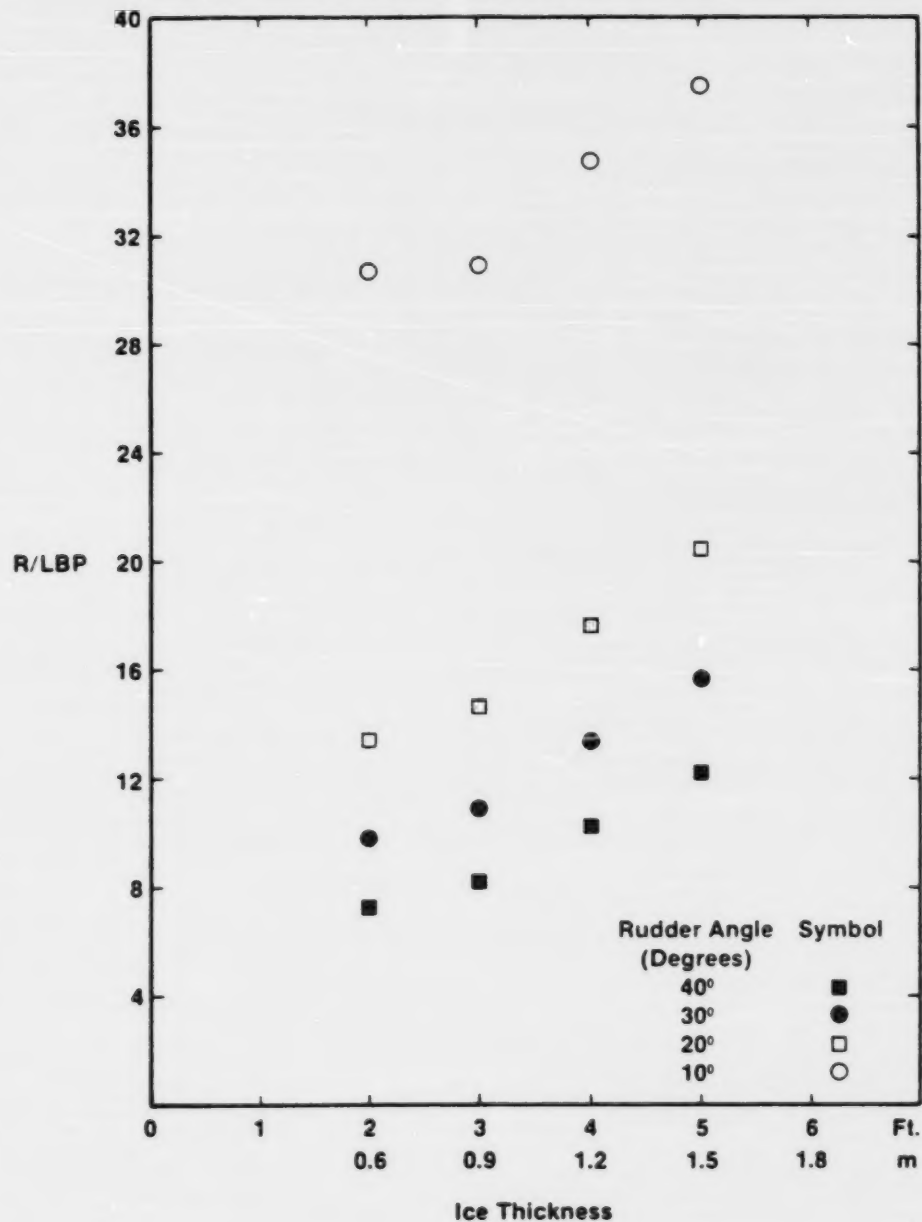


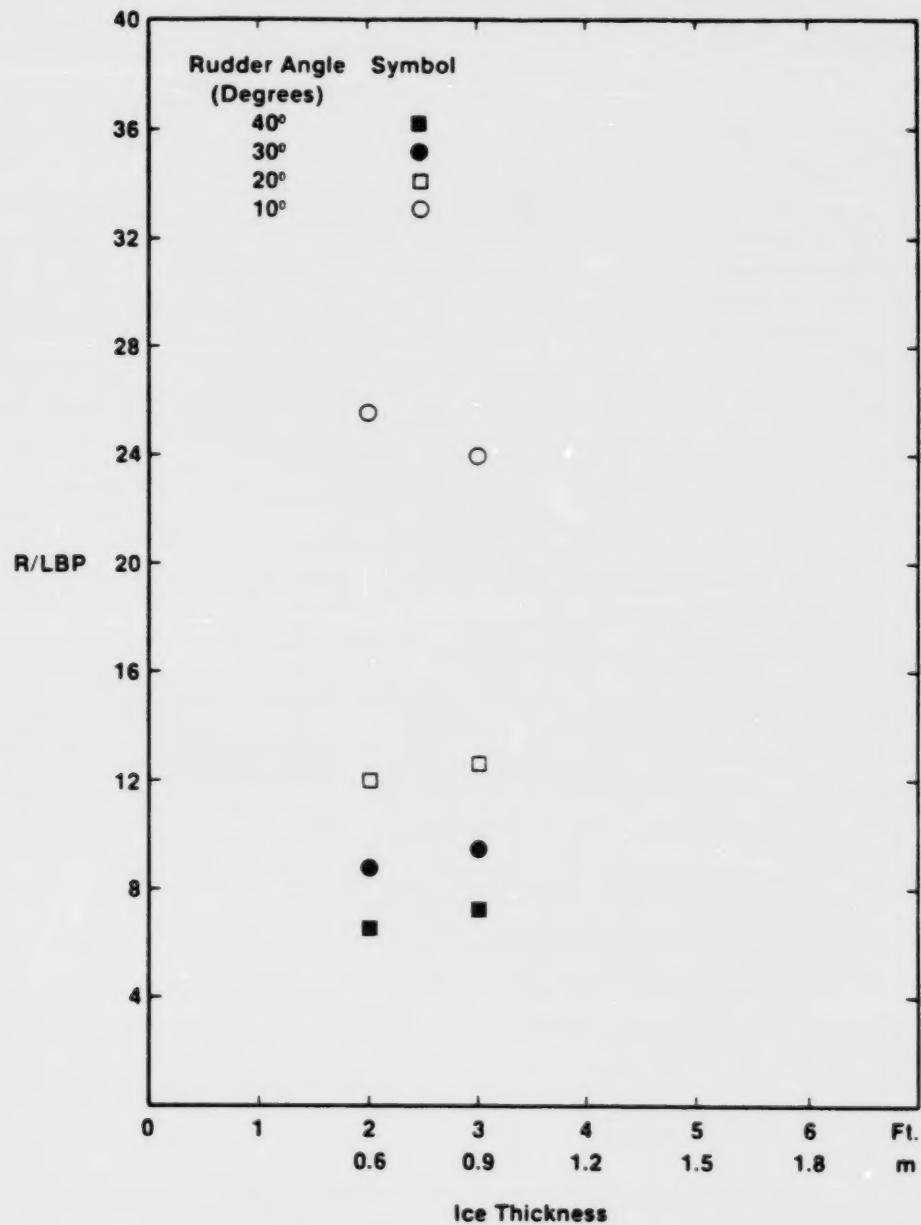
FIGURE 6.5

Polar Star: Predicted Turning Radius Per Unit LBP

Average Ice Flexural Strength : 300 Kpa

Power Level: 18000 SHP

Trapezoidal (2:1) Midbody Side Force Distribution



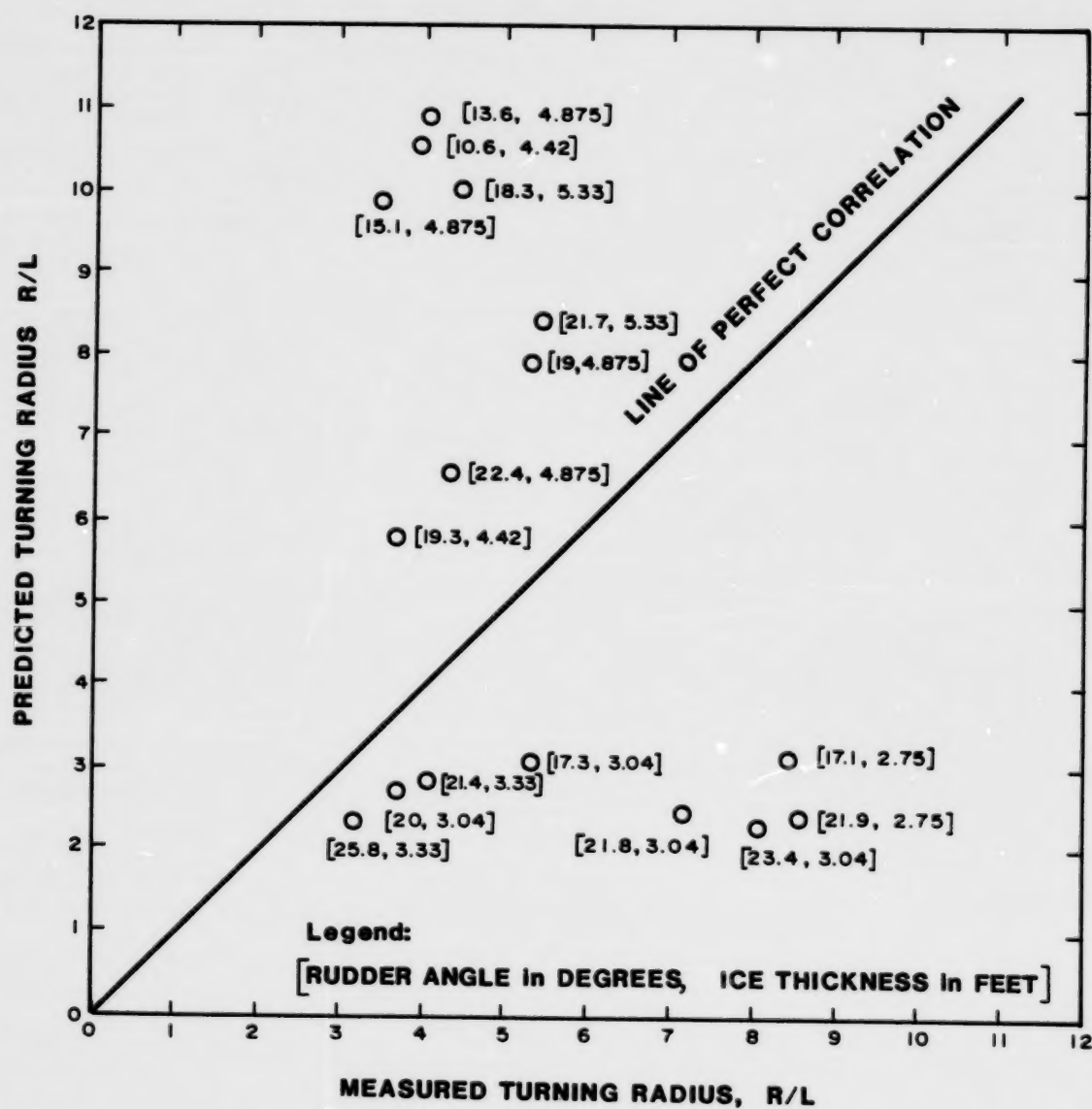
7. COMPARISON OF PREDICTIONS WITH MEASUREMENTS

7.1 Time-Domain (T-D) Prediction vs. Measurements

A number of predictions were made with the T-D model for the entire range of power levels as shown in Section 5.4. For comparison purposes, the model was further exercised with 32000 HP which represents the power level at which the trials were conducted. The computed turning radii (R/L) were compared with those obtained from measurements as shown in Figure 7.1. It is seen that the T-D model consistently under-predicted at lower ice thicknesses and over-predicted at higher ice thicknesses. In view of the thrust imbalance discussed in Section 4.2, the poor comparison was not unexpected for the tests carried out in ice of about .9 m thick. These had as much as 50% asymmetry in the thrust distribution. As the hull coefficients obtained from model test data represents thick ice with strength roughly two times higher than that in the field, one would expect the T-D model to over-predict the turning radius under those conditions. A second factor that contributes to poor comparison at twice thicknesses around 1.5 m is the fact that the actual thrust during the tests was mostly carried by the center shaft which makes the rudder more effective under those conditions. In the model, on the other hand, the thrust is assumed to be uniformly distributed among the three shafts. Further comparisons with data from other trials are necessary to validate the T-D model in its present form.

FIGURE 7.1

COMPARISON of MEASURED TURNING RADIUS
WITH PREDICTED TURNING RADIUS



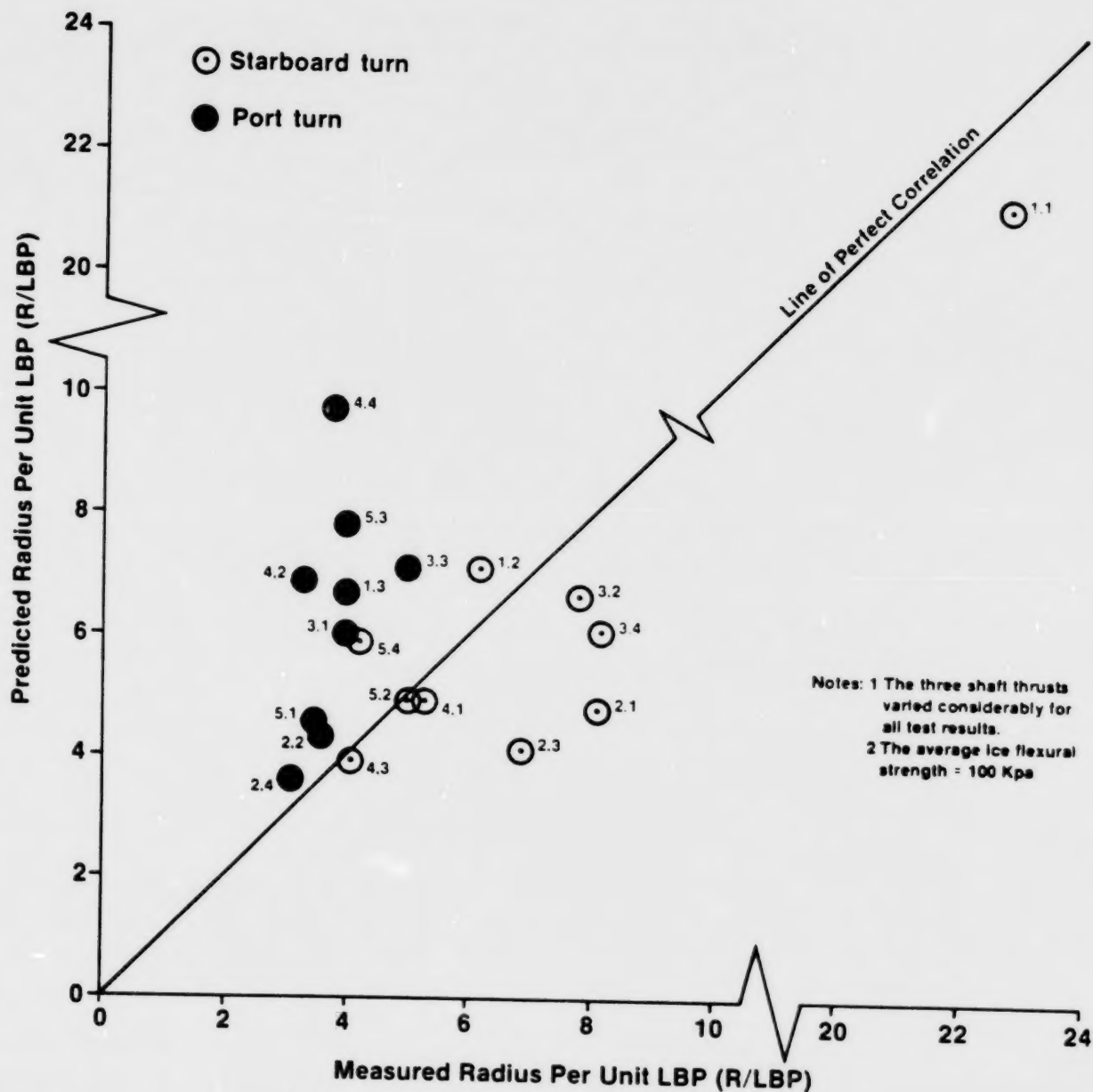
7.2 Canmar Model Prediction Vs. Measurement

The model was exercised to obtain the steady state turning radius of the POLAR STAR using the actual ship and ice conditions during the January 1985 full scale tests. The weak ice encountered during the full scale tests and the pronounced asymmetry in the developed thrust of the two outboard shafts were accounted for in the model. The straight ahead ship speed in unbroken level ice was assumed to be 1.18 times the average speed in the turn. From onboard observation and video recordings, it was difficult, if not impossible, to estimate with confidence where the midbody side force was effectively acting on the ship. The assumption that the midbody side force is acting at the midship is however, believed to be realistic.

The comparison of the predicted and measured turning radius per ship length is shown in Figure 7.2. From Figure 7.2, it is clear that the predicted turning radius is always greater than the corresponding measured values when the ship is turning to port. Irrespective of the ice thickness, rudder angle and power, the measured turning radius during the port turns vary only between 3.1 to 5.0 (R/L). The predicted turning radius for the starboard turns are much more sensitive to the ice thickness, rudder angle and power, varying from 3.6 to 9.7. On the other other hand, with the exception of two data points, the predicted turning radii are less than the corresponding measured values when the ship is turning to starboard. This systematic discrepancy is partly due to the influence of the propeller rotation (one left handed and two right handed) which tends to assist the ship to turn to port. The effect of the direction of propeller rotation has not been taken into account in the present model.

FIGURE 7.2
**COMPARISON BETWEEN PREDICTED &
MEASURED TURNING RADIUS**

Numerals below denote Test Number, Section Number
eg. 3, 2 = Test No. 3, Section No. 2



7.3 Shortfalls of T-D Model and Improvements Required

A number of shortfalls have been identified with the time-domain manoeuvring simulation model. These are discussed below:

i) The major inadequacy of the T-D model is the lack of specific model test data that can be directly applied to the case of the POLAR STAR. The data used in the present case were obtained from model tests of R-Class and Polar-7 hull forms and hence are not directly applicable to the POLAR STAR. The corrections applied to transform the data strictly accounts for the differences in the main particulars such as length and beam. Effect of bow geometry, block coefficient and such other parameters have not been taken into account. The present model uses hull derivatives that do not incorporate the effect of change in flexural strength of ice.

ii) The T-D model for the POLAR STAR in its present form takes into account equal thrust on the three propellers in the calculation of forward motion and its effect on the rudder. The distribution of the total thrust among the three propellers governs the effectiveness of the rudder. For example, a percentage distribution of 10-80-10 of the total thrust will generate more rudder "lift" than a 30-40-30 distribution. This effect is presently not taken into account in the model. In addition, the present model has no provision for incorporating an imbalanced thrust distribution such as that generated by the directions of rotation of the three screws as well as thrust imbalance generated by control system malfunctions and the non-equilibrium propeller loading in turn.

iii) The estimate of the speed in the turn is based on our approximate method of calculating the increase in resistance in the turn, which takes into account present full-scale trial data. The applicability of the model to other vessels is, therefore, limited unless similar trials data are available or can be acquired.

7.4 Shortfalls of Canmar Model and Improvements Required

The main assumptions and their effects on the predicted turning radius are reviewed in the light of the comparisons made in the previous section.

i) Hydrodynamic forces have been assumed to be small in the present model. This assumption is valid in thick ice. The magnitude of the error remains to be quantified.

ii) For conventional icebreaking hull forms, the bow geometry can be represented by a simple flat-plate wedge. The predicted turning radius is relatively more sensitive to changes in the value of the mean half waterline angle than the mean buttock angle of the bow. The predicted turning radius decreases as the mean half waterline angle increases and vice versa. On the other hand, the turning radius decreases with smaller mean bow buttock angles and vice-versa. It should be noted, however, that a short bow with a large half waterline angle breaks a narrower channel than a long bow. Thus, a long bow with a small half waterline angle allows for a wider channel and has lower resistance to turning in ice. This effect is not accounted for in the

present model.

iii) The turning radius is highly dependent on the location of the midbody side force which varies with ship design. As the location of the midbody side force moves further aft, the turning radius increases. It is suggested that the midbody side force for icebreakers with no distinct parallel midbody be assumed to act at its centre of gravity. For icebreakers with substantial parallel midbody, the midbody side force can be assumed to act at the aft end shoulder of the ship. For long ships, there may be a concentrated load at the aft shoulder of the parallel midbody which leads to the same effect as for icebreakers with parallel midbody. The force is then located at the aft end of the midbody.

iv) The total ice resistance in the straight ahead mode is concentrated on the ship bow. The predicted ice resistance acting on the ship bow is slightly higher since the frictional forces acting along the ship sides and bottom have been neglected. This has the effect of overpredicting the turning radius by the same proportion, i.e., a 5% overestimate of the ice resistance will result in a 5% higher turning radius.

v) The net asymmetric ice forces on the bow in the transverse direction is proportional to the difference in the volume of ice broken by the bow per unit time. In fact the force on each side of the bow changes when the direction of movement of the bow changes. This is the result of the change in the relative angle of ice interaction.

vi) The ship centre of rotation is at its centre of gravity. The turning radius decreases if the centre of rotation is forward of the centre of gravity and increases if the centre of rotation is aft of the centre of gravity of the ship during steady turning.

vii) In the steady state, the ship is assumed to turn about a fixed centre of the turning circle. This assumption has no direct influence on the turning radius predicted from the model. To summarize, the prediction capability of the model can be greatly improved by taking into account the following:

- 1) A better estimate of the location of the midbody side force eg. by calibration with other full scale data.
- 2) A better estimate of the rudder lift force taking into account the effects of the propeller race, the wake and the drift angle. These are presently taken into account in the rudder hydrodynamics model, but will require independent validation.
- 3) The direct influence of the propeller on turning.
- 4) The effect of wind and current.
- 5) The hydrodynamic forces on the ship while turning in thin ice.
- 6) A better estimate of the location of the centre of rotation.

8. CONCLUSIONS AND RECOMMENDATIONS

A number of general conclusions can be drawn from the Antarctic manoeuvring trials:

- ° The instrumentation system used met all the requirements of the manoeuvring tests and the data reduction and analysis software developed and implemented can be called a standard system for future applications.
- ° Out of twenty (20) manoeuvres carried out, nineteen (19) produced good quality data on vessel performance in the turn. Steady turns were achieved with all 16 channels of data working satisfactorily.
- ° The microwave position fixing system used to obtain the vessels turning trajectory performed well. The only "blackouts" experienced in the vessel position data were those associated with the "shadow" effect of the ship's mast.
- ° One of the major problems in interpreting the data was that associated with the non-uniform thrust distribution in the three propellers. The pronounced asymmetry in the thrust of the two outboard shafts accounted for the shorter turning radius to port than to starboard.
- ° Although no difficulty was experienced in manoeuvring in thick but very weak ice of the Antarctic, this is not entirely consistent with the operational experience with the same class icebreaker in stronger ice in the Arctic.
- ° The time-domain mathematical model of vessel manoeuvring in level unbroken ice consistently over-predicted the steady turning radius. A number of factors contributed to this discrepancy: the hull derivative coefficients which were extracted from model test data of icebreaking hull forms do not account for changes in flexural strength. The model data pertains to 400 kPa conditions, while the trials data relates to an average strength of 180 kPa.
- ° The Canmar model predicts greater turning radius for turns to port and tends to under estimate the turning radius for turns to starboard when compared to the corresponding full scale measurements. This systematic discrepancy is believed to be partly due to the direct influence of the propellers, which is not accounted for in the present model. The sensitivity analysis of the model shows that the predicted turning radius is very sensitive to the location of the midbody side force, the estimated rudder lift force and the bow geometry, especially the mean half waterline angle.

The following specific conclusions can be drawn with reference to the manoeuvring trials:

- ° Using all diesel power (16% - 55% - 29% shaft thrust distribution), the turn to port occurred in 350 to 400 m radius, which is about 1/2 the distance required for the starboard turn (700 to 800 m) with a thrust distribution of (18% - 50% - 32%).
- ° In 1.08 m of level ice, a 30% reduction in ship speed was observed when turning compared to straight ahead icebreaking at the same total propeller thrust.
- ° In 1.2 to 1.5 m thick level ice, using gas turbine power (20,000) on the centre shaft, the POLAR Class can turn with a radius of 3 to 4 times its waterline length. This is an exceptionally good capability compared to the RADISSON CLASS and other icebreakers in the same ice thickness.

Based on the full scale trials of the POLAR STAR and the comparison of the results, the following recommendations can be made:

- ° With the 19 data points gathered as part of the 1985 Antarctic deployment, this is the first set of manoeuvring data collected aboard the Polar Class. However, the data were limited in view of the propeller thrust imbalance, power level and the ordered helm. A second year of testing is essential to complete the original objective set forth in the test plan.
- ° As part of the 1985 Antarctic deployment, it was hoped that test time would be allocated to conduct a series of backing and filling tests and a series of turning out of a broken channel tests. Unfortunately, available testing time did not allow any of these tests to be performed. It is, therefore, recommended that they be conducted as part of the 1986 Antarctic deployment.
- ° For a complete understanding of the manoeuvring characteristics of the POLAR Class vessels in level unbroken ice, it will be necessary to carry out further controlled tests under the following conditions:
 - Steady turning tests at rudder angles of 30 and 40 degrees.
 - Turning tests with uniform thrust distribution as well as centre shaft thrusts of 30, 60 and 90% of total.
 - Manoeuvring with screws - constant centre shaft thrust and rudder angle with wing shaft thrust varying from 10 and 40%.
- ° The manoeuvrability of the POLAR Class hull forms in no way reflects the performance of parallel sided merchant hull forms. There is strong need for manoeuvring data in strong ice with these vessels.

9. REFERENCES

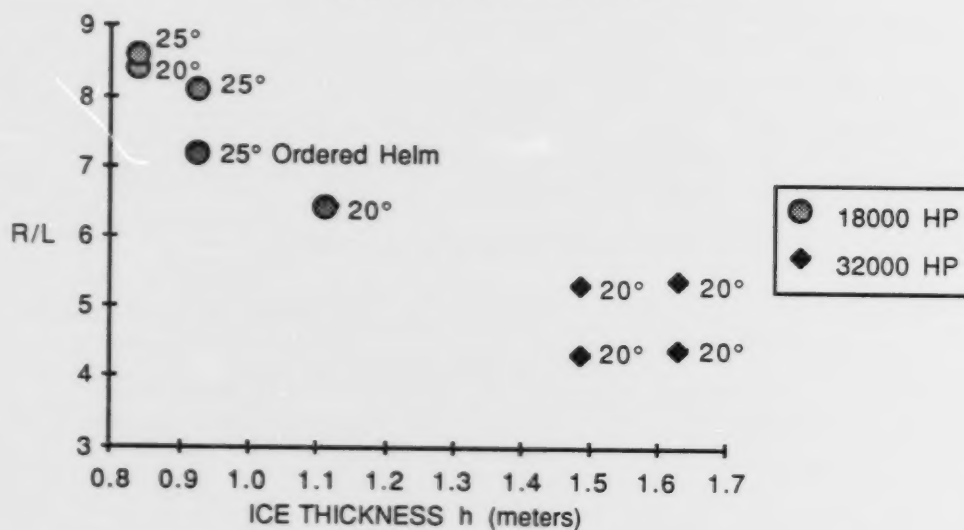
- [1] Icebreaker Model Manoeuvring Test Results, Arctec Canada Limited Report #15E, October 1973.
- [2] Arctic Deployment of USCGC POLAR STAR Winter 1982, Arctec Canada Limited Report FR937C.2, September 1982.
- [3] Ship Icebreaking Dynamics Testing Aboard USCGC POLAR STAR in Antarctica, Volume I Technical Report, Volume II Appendices, Arctec Inc. Report 1060C-2, April 1985.
- [4] Arctic Deployment of USCGC POLAR STAR Winter 1982, Volume IV, Ice Loads on Steering Gear Systems, Arctec Canada Limited, FR937C.2, Sept. 1982.

APPENDIX A

FULL SCALE OPEN WATER AND ICE MANOEUVRING DATA

Figure A-1
VARIATION of TURNING RADIUS with ICE THICKNESS

(a) STARBOARD TURNS



(b) PORT TURNS

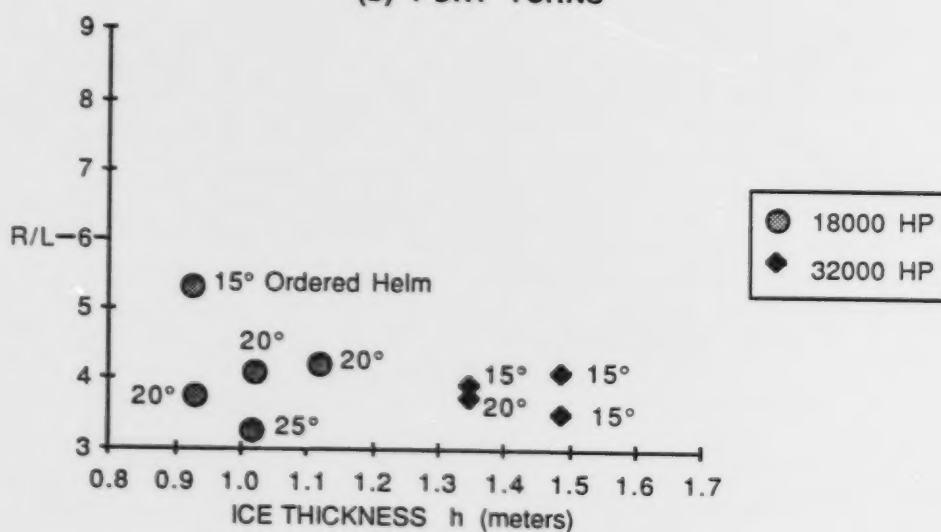
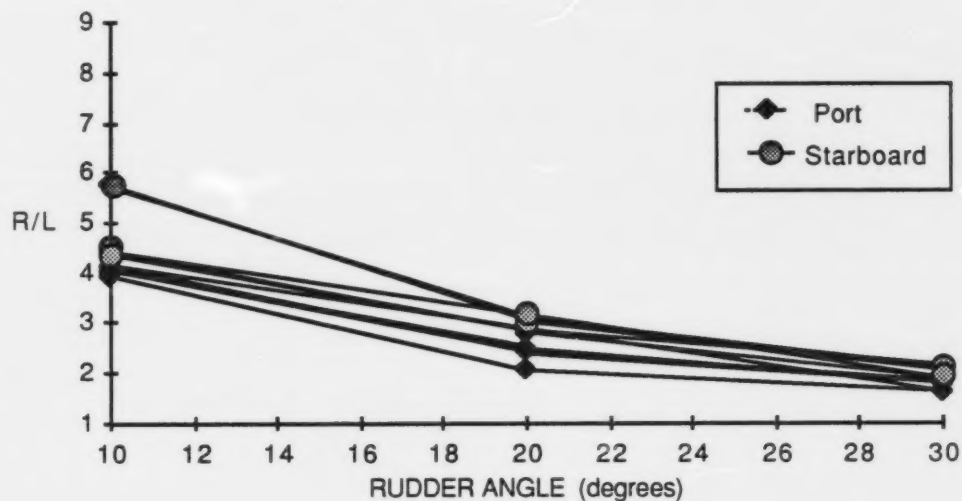


Figure A-2
VARIATION of TURNING RADIUS with RUDDER ANGLE

(a) OPEN WATER DATA ONLY



(b) OPEN WATER and ICE DATA

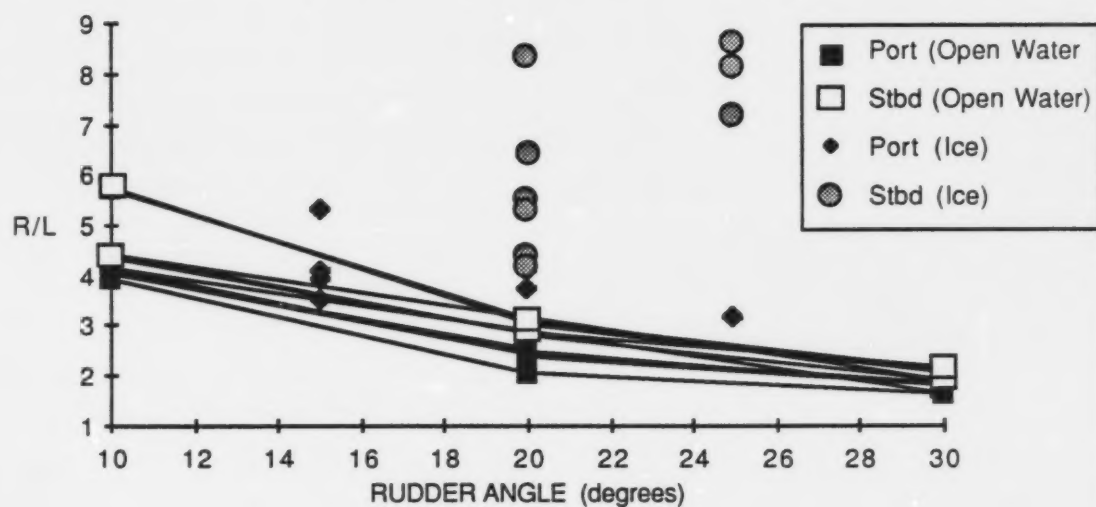
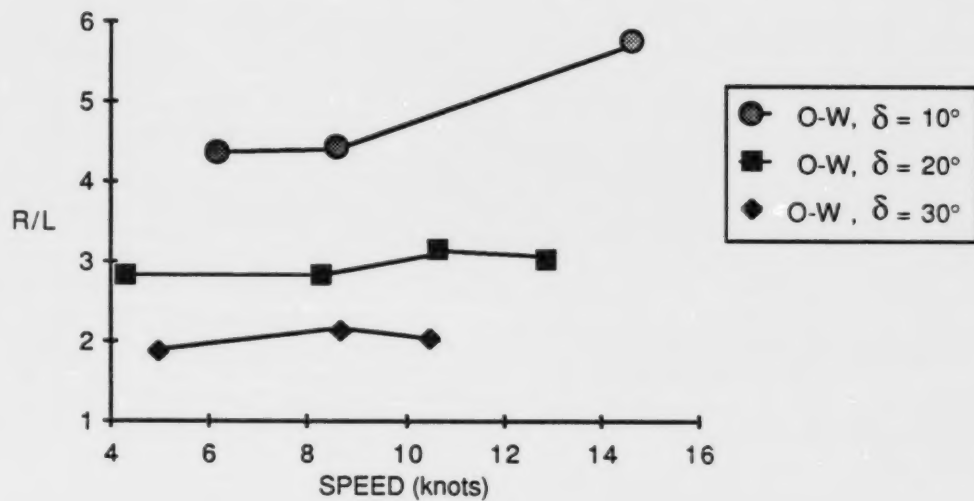


Figure A-3
VARIATION of TURNING RADIUS with SPEED in OPEN WATER

(a) STARBOARD TURNS



(b) PORT TURNS

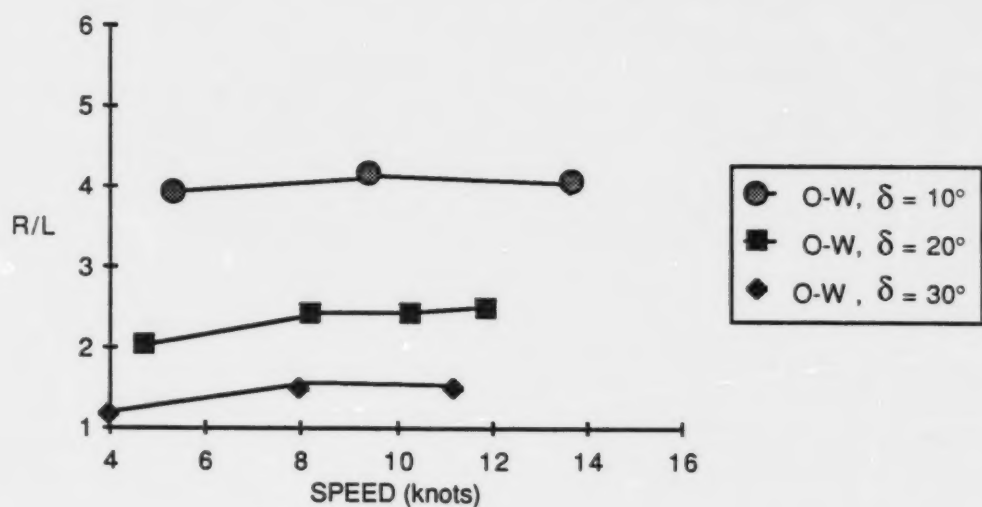
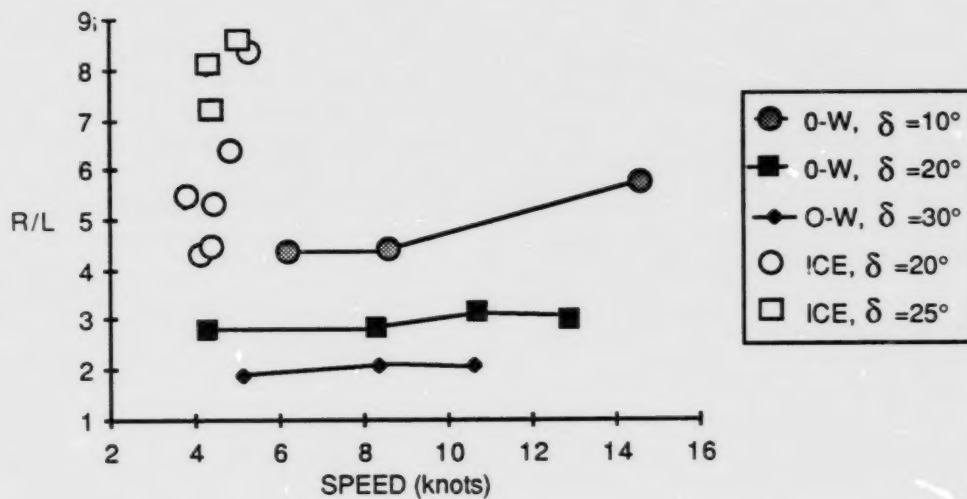


Figure A-4
VARIATION of TURNING RADIUS with SPEED
in OPEN WATER and ICE

(a) STARBOARD TURNS



(b) PORT TURNS

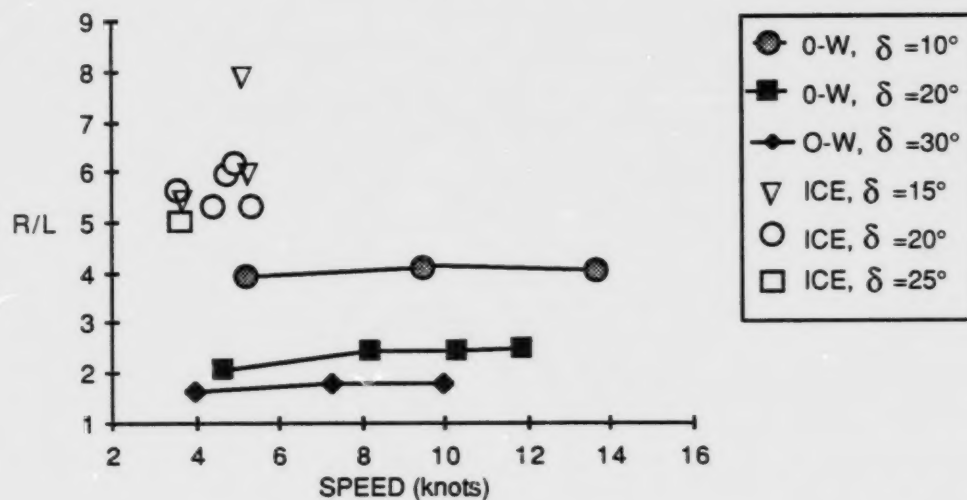
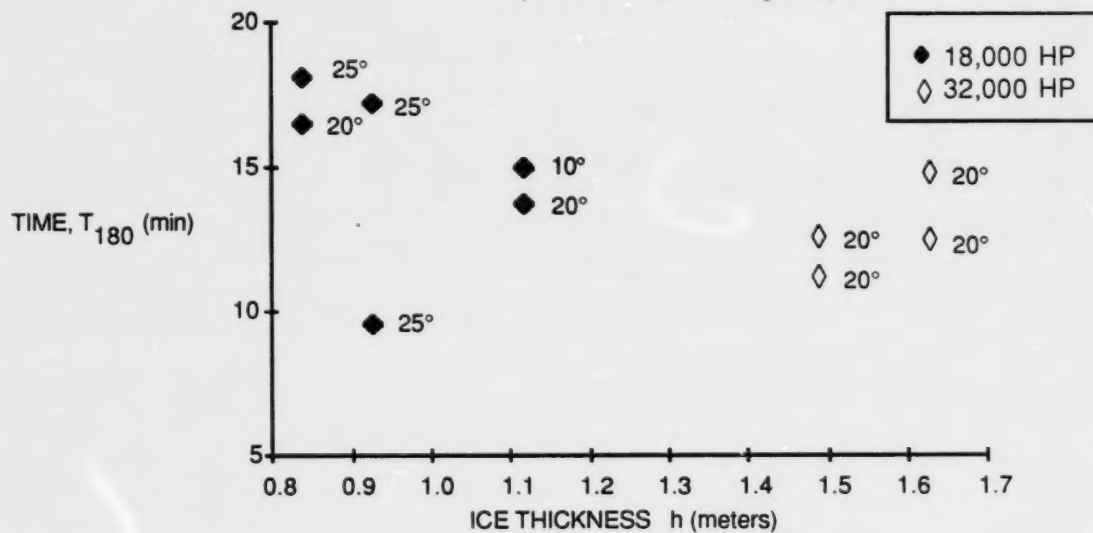


Figure A-5
TIME TAKEN to TURN 180 DEGREES

(a) STARBOARD TURNS
 (Ordered helm in degrees)



(b) PORT TURNS
 (Ordered helm in degrees)

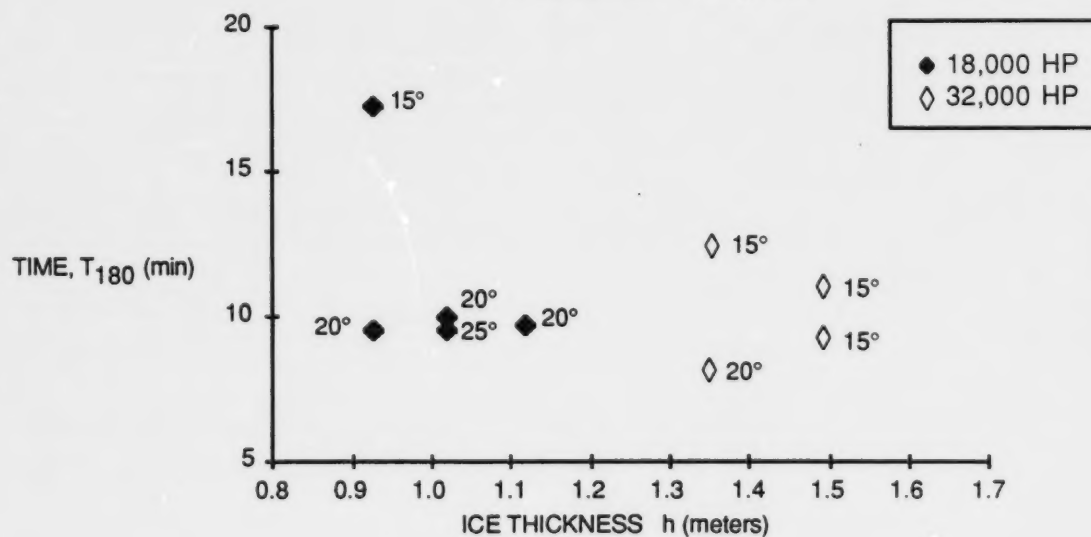


Figure A-6
RATE of TURN

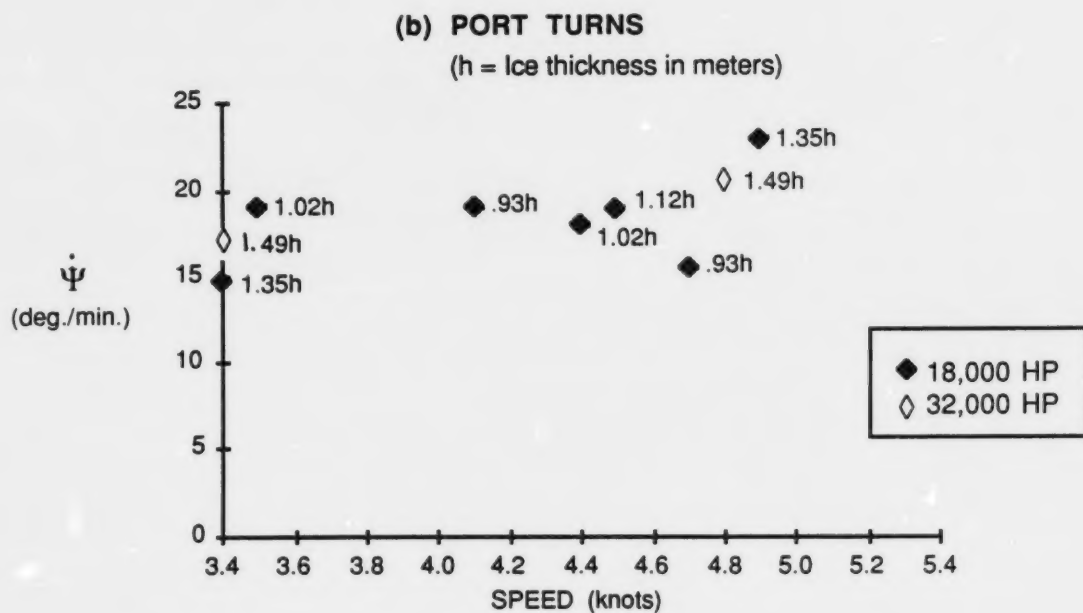
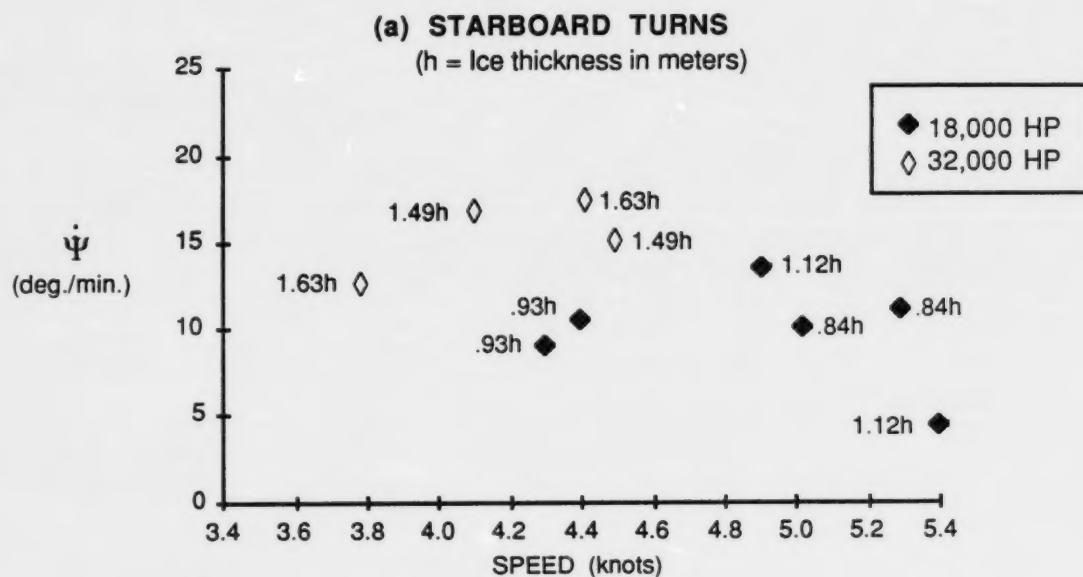
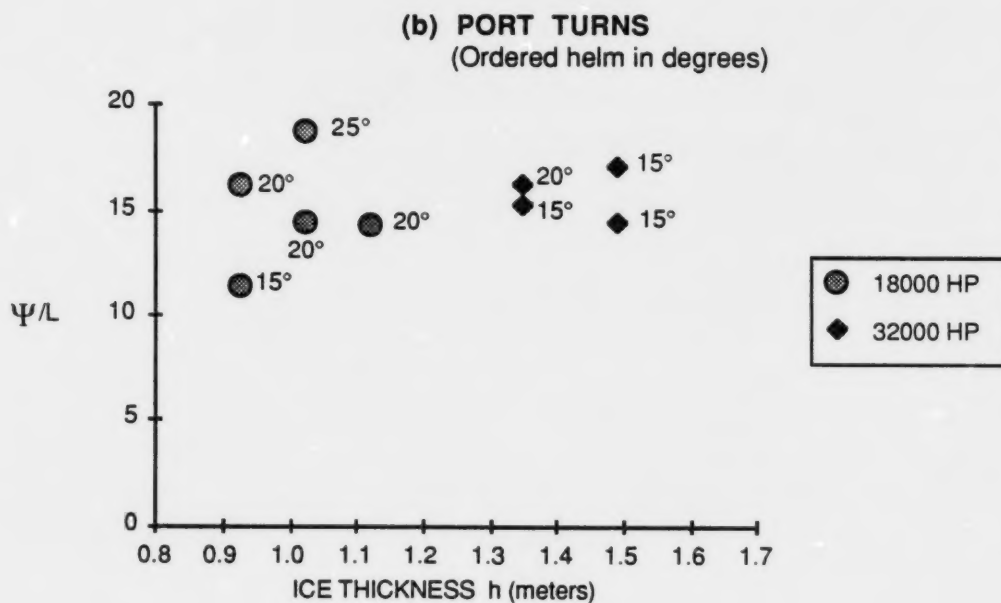
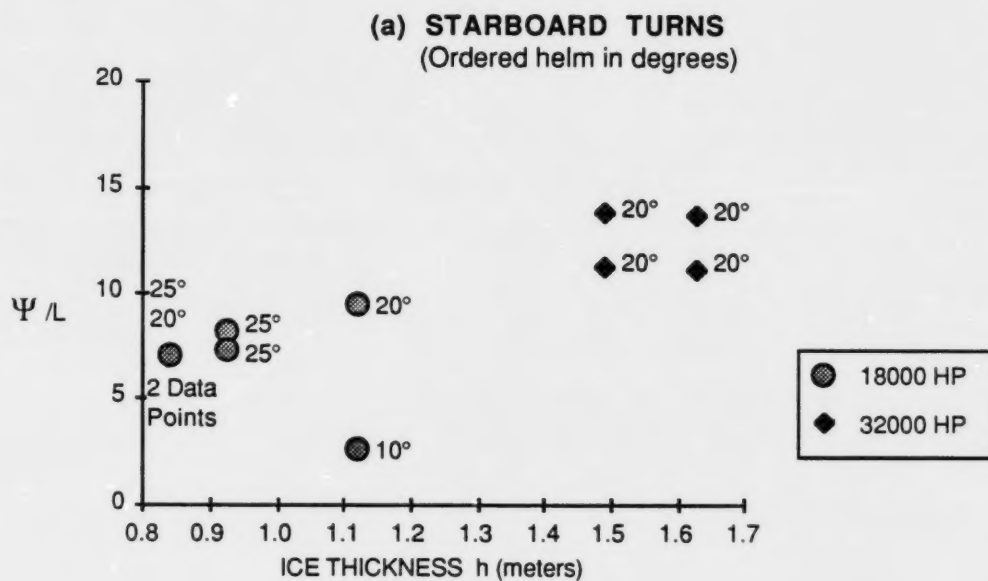


Figure A-7
CHANGE in HEADING PER SHIP LENGTH of ADVANCE



APPENDIX B

TIME-DOMAIN MANOEUVRING MODEL

BASIS OF TIME-DOMAIN MANOEUVRING SIMULATION MODEL

METHOD OF OBTAINING DERIVATIVE COEFFICIENTS

SOURCE OF DERIVATIVE COEFFICIENTS

X - EQUATION

Y - EQUATION

N - EQUATION

NOMENCLATURE

REFERENCES

BASIS OF TIME-DOMAIN MANOEUVRING SIMULATION MODEL

The mathematical model describing the motion of a ship in the horizontal plane has been well developed in the past. To obtain realistic simulations of maneuvers such as tight turns and to predict the performance of a dynamically unstable ship, it becomes necessary to develop and solve a set of nonlinear equations of ship motion. The derivation of a nonlinear mathematical model is well explained by Abkowitz [1]. The third order Taylor expansion of the equation becomes:

$$\begin{aligned} X &= (m - X_{\dot{u}}) \dot{u} \\ Y &= (m - Y_{\dot{v}}) \dot{v} + (m x_G - Y_{\dot{r}}) \dot{r} \\ N &= (m x_G - N_{\dot{v}}) \dot{v} + (I_z - N_{\dot{r}}) \dot{r} \end{aligned} \quad (1)$$

The forces, X and Y and the moment N are functions of the ship, ice and motion properties. These are expressed as:

$$X, Y, N = f(B, L, C_B, \dots; \rho_i, \rho_w, h, \sigma_f, E., u, v, r, \delta, \dot{u}, \dot{v}, \dot{r}, \delta, \dots)$$

ship particulars ice properties motion parameters

For a given ship and prescribed ice properties, these equations can simply be expressed as follows by neglecting the effects of change in acceleration on the forces and moment experienced by the ship. The only forces and moment that are associated with accelerations (other than rigid body inertia) are assumed to be the hydrodynamic inertial reactions of the surrounding fluid represented by the terms:

$$X_{\dot{u}} \dot{u}, Y_{\dot{v}} \dot{v} \text{ and } N_{\dot{r}} \dot{r}$$

as shown by Newman [2].

Then we have:

$$\begin{aligned} X, Y, N &= f(u, v, r, \delta) \text{ or} \\ &= X, Y, N(u, v, r, \delta) \end{aligned} \quad (2)$$

In order to define the above functions in terms of variables u, v, r , and δ we expand the above functions using the third order Taylor series, neglecting the second or higher order acceleration terms, and also the cross-coupling terms between acceleration and velocity parameters. Then the above equation becomes:

$$X(u, v, r, \delta) = X_* + X_u \Delta u + \frac{1}{2} X_{uu} \Delta u^2 + \frac{1}{6} X_{uuu} \Delta u^3 + \frac{1}{2} X_{vv} v^2 + \left(\frac{1}{2} X_{rr} + mx_G \right) r^2 + \frac{1}{2} X_{\delta\delta} \delta^2 + (X_{vr} + m) vr + X_{v\delta} v\delta + X_{r\delta} r\delta \quad (3)$$

$$Y(u, v, r, \delta) = Y_* + Y_u \Delta u + Y_{uu} \Delta u^2 + Y_v v + \frac{1}{6} Y_{vvv} v^3 + \frac{1}{2} Y_{vrr} vr^2 + \frac{1}{2} Y_{v\delta\delta} v\delta^2 + (Y_r - mu) r + \frac{1}{6} Y_{rrr} r^3 + \frac{1}{2} Y_{rvv} rv^2 + \frac{1}{2} Y_{r\delta\delta} r\delta^2 + Y_\delta \delta + \frac{1}{6} Y_{\delta\delta\delta} \delta^3 + \frac{1}{2} Y_{\delta vv} v\delta^2 + \frac{1}{2} Y_{\delta rr} \delta r^2 + Y_{vr\delta} vr\delta \quad (4)$$

$$N(u, v, r, \delta) = N_* + N_u \Delta u + N_{uu} \Delta u^2 + N_v v + \frac{1}{6} N_{vvv} v^3 + \frac{1}{2} N_{vrr} vr^2 + \frac{1}{2} N_{v\delta\delta} v\delta^2 + (N_r - mx_G u) r + \frac{1}{6} N_{rrr} r^3 + \frac{1}{2} N_{rvv} rv^2 + \frac{1}{2} N_{r\delta\delta} r\delta^2 + N_\delta \delta + \frac{1}{6} N_{\delta\delta\delta} \delta^3 + \frac{1}{2} N_{\delta vv} \delta v^2 + \frac{1}{2} N_{\delta rr} \delta r^2 + N_{vr\delta} vr\delta \quad (5)$$

The derivative coefficients in the above equations:

$$X_{\delta\delta u}, X_{vru}, X_{v\delta u}, X_{r\delta u}, Y_{vu}, Y_{vuu}, Y_{ru}, Y_{ruu}, Y_{\delta uu}, N_{vu}, N_{vuu}, N_{ru}, N_{ruu}, \text{ and } N_{\delta uu},$$

which represent the change with speed, have been found to be negligible in open water tests. We, therefore, arbitrarily assume these coefficients are also negligible in an ice environment and thus cross them out in the above equations. We combine the Equations (1) and (2) and solve for u, v and r . Then the solutions are:

$$\begin{aligned} \dot{u} &= \frac{X(u, v, r, \delta)}{(m - X_u)} \\ \dot{v} &= \frac{(I_z - N_r) Y(u, v, r, \delta) - (mx_G - Y_r) N(u, v, r, \delta)}{(m - Y_v) (I_z - N_r) - (mx_G - N_v) (mx_G - Y_r)} \\ \dot{r} &= \frac{(m - Y_v) N(u, v, r, \delta) - (mx_G - N_v) Y(u, v, r, \delta)}{(m - Y_v) (I_z - N_r) - (mx_G - N_v) (mx_G - Y_r)} \end{aligned} \quad (6)$$

In order to determine whether an icebreaker will maintain a straight line path without using the rudder after a small disturbance in ice (such as that due to impact against a multi-year floe of moderate size), it is necessary to examine the *stability roots*. These are obtained by solving the differential equations (1) and the first order Taylor series expansion of equations (2) and are given by:

$$\left. \begin{matrix} \sigma_1 \\ \sigma_2 \end{matrix} \right\} = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \quad (12)$$

$$\sigma_3 = \frac{X_u}{(m - X_G)}$$

where:

$$\begin{aligned} A &= (m - Y_{\dot{\psi}}) (I_z - N_r) - (mx_G - Y_r) (mx_G - N_{\dot{\psi}}) \\ B &= -(m - Y_{\dot{\psi}}) (N_r - mx_G u_1) - (I_z - N_r) Y_v + \\ &\quad (mx_G - Y_r) N_v + (mx_G - N_{\dot{\psi}}) (Y_r - mu_1) \\ C &= Y_v (N_r - mx_G u_1) - N_v (Y_r - mu_1) \end{aligned} \quad (13)$$

For directional stability, the values of σ_1 , σ_2 , σ_3 have to be negative.

For a normal ship, σ_3 will always be negative since $X_{\dot{u}}$ and X_u are negative. In order for σ_1 , σ_2 to be negative (13) can be evaluated by examining each factor. It is clear that $Y_{\dot{\psi}}$ is a negative number. $Y_{\dot{\psi}}$ for normal ships in open water is usually a large negative number equivalent to about twice the ship's mass. N_r is also a large negative number, approximately twice as much as the ship's moment of inertia. Y_r and N_v can be positive if the forces and moments are more dominant at the stern than the bow and negative if the forces and moments are dominant at the bow. Therefore, these numbers are relatively small. This same reasoning holds for ships operating in ice. The magnitude of each factor just described will be greater. Therefore the sign of A is always positive. The sign of B can also be evaluated in the same manner. N_r and Y_v are always negative numbers for a ship operating in open water and these will be even more negative in ice. N_v and Y_r are either positive or negative depending on the dominance of forces and moments of the ship ends. If all the factors in equation (13) for B are put together as previously described, the sign of B will turn out to be positive. Therefore, the criteria for σ_1 , σ_2 to be negative is based on C being positive.

A typical automatic rudder control system includes yaw-angle (ψ) and yaw-rate ($\dot{\psi}$) controls and a rudder response-time constant (t_r) where the rudder angle δ satisfies the following differential equations:

$$\delta + t_r \dot{\delta} = a(\psi - \psi_d) + b\dot{\psi} \quad (7)$$

where ψ_d is the desired heading angle of the ship.

Linear and angular velocities of the ship with respect to the earth-fixed axes are obtained in terms of body-axis velocity components as:

$$\begin{aligned} \dot{\psi}(t) &= r \\ \dot{y}_0(t) &= u \sin \psi + v \cos \psi \\ \dot{x}_0(t) &= u \cos \psi - v \sin \psi \end{aligned} \quad (8)$$

Position and orientation of the ship are readily obtained, from the initial conditions and through integration of the above equation, as:

$$\begin{aligned} \psi &= \psi(0) + \int_0^t \dot{\psi} dt \\ y_0 &= y_0(0) + \int_0^t \dot{y}_0 dt \\ x_0 &= x_0(0) + \int_0^t \dot{x}_0 dy \end{aligned} \quad (9)$$

We can further compute u , v and r at time $(t + \Delta t)$ from the knowledge of u , v , r , and δ at the time t using the following first order Taylor series expansion:

$$\begin{aligned} u(t + \Delta t) &= u(t) + \Delta t \dot{u}(t) \\ v(t + \Delta t) &= v(t) + \Delta t \dot{v}(t) \\ r(t + \Delta t) &= r(t) + \Delta t \dot{r}(t) \end{aligned} \quad (10)$$

The turning radius is computed from the following relationship (when a ship reaches the steady turning phase; i.e. $\dot{v} = \dot{r} = 0$):

$$R = \frac{V}{r(t)} \quad \text{when } \dot{r}(t) = \dot{v}(t) = 0, u = \text{constant} \quad (11)$$

In first order terms, the expressions for the forces and moment can be written as:

$$Y = Y_v v + Y_r r + Y_{\dot{v}} \dot{v} + Y_{\dot{r}} \dot{r} + Y_{\delta} \delta$$

$$N = N_v v + N_{\dot{v}} \dot{v} + N_r r + N_{\dot{r}} \dot{r} + N_{\delta} \delta$$

$$X = T_t - R_t$$

where T_t and R_t are the total propeller thrust and

$$Y_v = Y'_v \frac{\rho}{2} L^2 u$$

$$Y_r = Y'_r \frac{\rho}{2} L^3 u$$

$$Y_{\dot{v}} = Y'_{\dot{v}} \frac{\rho}{2} L^3$$

$$Y_{\dot{r}} = Y'_{\dot{r}} \frac{\rho}{2} L^4$$

$$Y_{\delta} = Y'_{\delta} \frac{\rho}{2} L^2 u^2$$

$$N_v = N'_v \frac{\rho}{2} L^3 u$$

$$N_{\dot{v}} = N'_{\dot{v}} \frac{\rho}{2} L$$

$$N_r = N'_r \frac{\rho}{2} L^4 u$$

$$N_{\dot{r}} = N'_{\dot{r}} \frac{\rho}{2} L^5$$

$$N_{\delta} = N'_{\delta} \frac{\rho}{2} L^3 u^2$$

The equations for level ice resistance based on full-scale data were obtained from [5]. This now combines earlier data with those obtained from January '85 trials. The equation for resistance in level ice of 100 kPa strength is:

$$R = 512 h^2 + 107 h V_s \quad \text{kilo-Newtons}$$

where h = ice thickness in metres
 V = ship speed in m/s.

The thrust developed by the propellers has been estimated from available data on Propulsion Performance. For the POLAR STAR full scale tow rope pull data were used. The propeller thrust vs. ship speed characteristics have been determined for three power levels:

Power 1	60000 HP
Power 2	40000 HP
Power 3	18000 HP

For each Power level the following relationships have been determined:

$$TP = R + B \times V_s$$

$$R_o = C_1 \times V_s + C_2 \times (V_s)^2 + C_3 \times (V_s)^3$$

where TP = Tow Rope Pull in kN

R_o = Openwater resistance in kN

V_s = Ship speed in kt

A, B, C_1 , C_2 , C_3 are coefficients

The thrust-deduction at relatively high propeller loadings at low speeds was for both ships estimated from:

$$t = 0.06 + 0.01 \times V_s$$

The total propeller thrust was then calculated from:

$$T = (TP + R_o) / (1 - t)$$

The coefficients for both ships are given as follows:

Tow Rope Pull Coefficients

Power	1	2	3
A	4500	3200	1870
B	-176	-129	-102

Openwater Resistance Coefficients

C_1	3.4
C_2	0.73
C_3	0.053

With the above given equations the total propeller thrust can be computed for each of the given power levels at the desired ship speed.

Predictions for any type of ahead manoeuvre can be made with the known rudder and propeller characteristics. Table B.1 below lists the required parameters of propeller steering and propulsion systems.

The derivative coefficients in Equations (3), (4), and (5) will have to be determined from model tests under controlled conditions and also possibly from the available theoretical methods in ice mechanics.

TABLE B.1

SHIP PARTICULARS REQUIRED FOR ESTIMATION OF
RUDDER INDUCED HULL FORCE AND MOMENT COEFFICIENTS

RUDDERS	PROPELLERS	SHIP
Number	Number	Maximum Speed
Section	Pitch/Diameter	Beam at Rudder
Tip Shape	Wake Factor	Draft at Rudder
Aspect Ratio	E.A.R.	
Area	Diameter	
Rudder Height	RPM	
Rudder Length	Distance to Rudder	
Torque Arm		
Bending Moment Arm		
Thickness/Chord Ratio		
Rudder Area Ratio		
Rudder Offset		
Distance between Rudders		

Method of Obtaining Derivative Coefficients

There are two fundamentally different options for determining the coefficients in the above equations of motion. The usual approach is to regard equations (1 - 6) as a "mathematical model" and to use experimental data for the coefficients. Most appropriate in this context are captive model tests where the motions of the model are prescribed, and the forces measured directly. Alternatively, theoretical methods can be used in a self-contained manner if adequate methods are available.

Indirect experimental methods that provide information on hull force and moment derivatives are easy to apply to the prediction of manoeuvring performance. Among these, the planar motion mechanism, oscillator, and rotating arm methods are considered. Although the test results obtained using the planar motion mechanism (PMM) can provide the most complete information on the hull force and moment derivatives, the construction of a PMM system suitable for ice tests, and the reduction of the data obtained during the PMM tests in ice is expected to be complex and costly. In addition, the statistical time-varying nature of icebreaking forces would complicate analysis of such tests where turning rate is constantly varying. For the same reason, oscillation techniques are also ruled out. Consequently, the rotating arm test method is adopted where a ship model is towed along a segment of a circle.

Two different types of tests are suggested; one is a straight-line test and the other a rotating test. In the straight-line tests the models are towed at constant velocity along a straight line parallel to the basin with a drift angle varying between - 3 and 5 degrees. This straight-line towing of a model with a drift angle generates a transverse velocity component and thus provides the data to plot the forces and moments against the transverse speeds. The distance of travel for each run is about two ship lengths. In the rotating tests, the models are towed along an arc segment by the rotating arm. This rotating generates a pure yaw angular velocity in the model. The rotating tests thus provide the data to plot the longitudinal forces and moments versus the yaw angular velocity. (See Figure B.1).

The scaling factors will be based on Froude modelling, which essentially means that the significant forces are those due to gravity, inertia, ice failure and friction. All forces, therefore, scale by λ^3 , where λ is the geometric scale factor.

The following measurements are required during the tests:

- ° longitudinal and transverse forces on the hull
- ° hull moment
- ° forward speed of the towing carriage
- ° rotating arm revolutions to calculate yaw angular velocity
- ° drift angle
- ° ice crushing (indentation) and bending strengths
- ° ice thickness along model track.

TYPICAL STRAIGHT LINE AND ROTATING TEST SEQUENCE

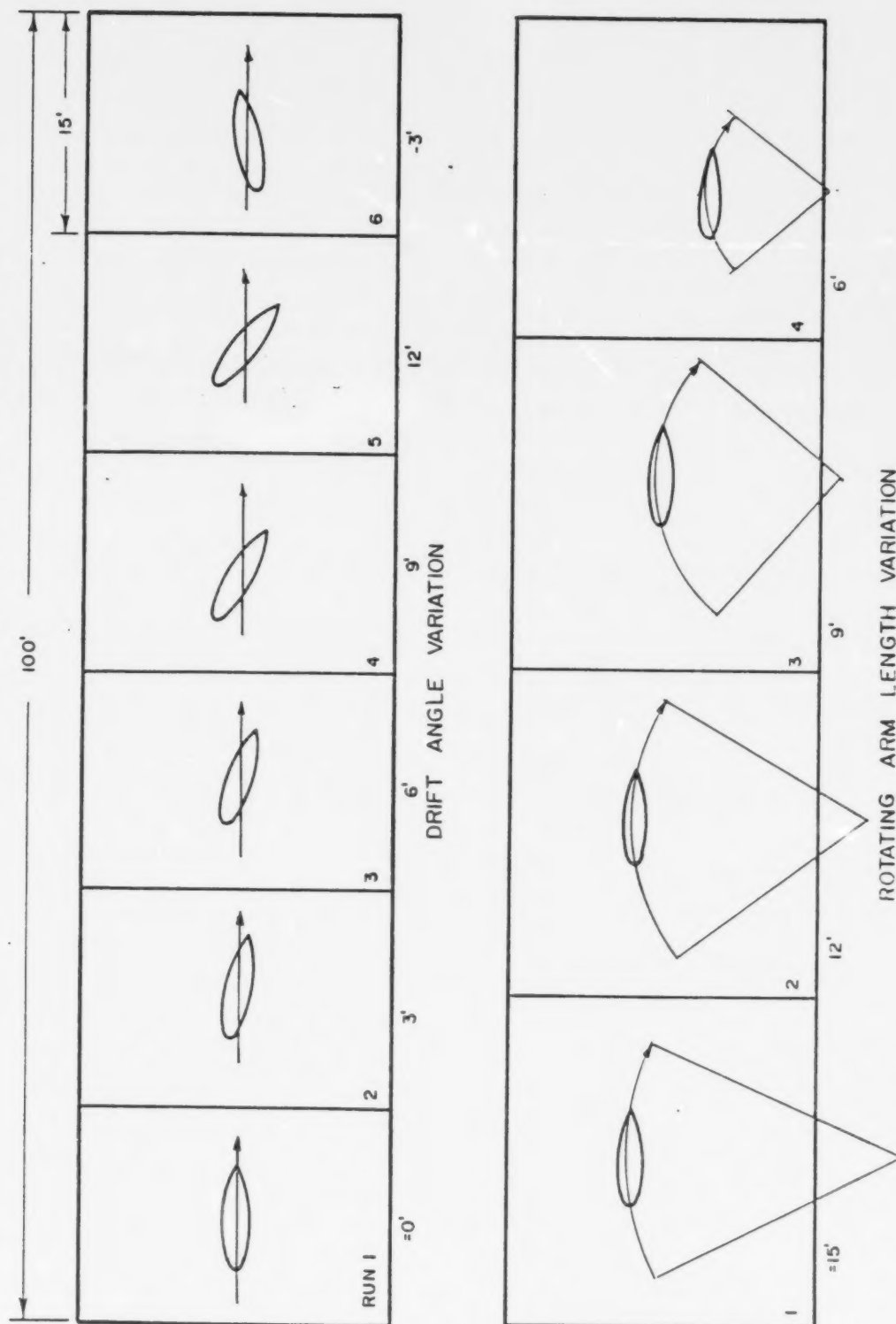


FIGURE B.1

The test data is best presented in nondimensional form. Nondimensionalizing data has several advantages. First, the nondimensional data have the same values for both the model and full-scale prototype and thus the analysis of model test data can be directly related to the full-scale prototype analysis. Second, the comparison of the model test data obtained in different environments during the tests becomes possible since the nondimensional data has been normalized. Third, several experimental variables can be combined to form one, thus achieving a reduction in the number of test variables.

In the case of straight line test:

$$\frac{Y}{\rho g B h^2} = f \left[\frac{v}{\sqrt{g h}}, \frac{\sigma_f}{\rho g h}, C_B, L/B \right]$$

$$\frac{N}{\rho g B L h^2} = f \left[\frac{v}{\sqrt{g h}}, \frac{\sigma_f}{\rho g h}, C_B, L/B \right]$$

and in the case of rotating arm tests:

$$\frac{Y}{\rho g B h^2} = f \left[\frac{r}{\sqrt{g/h}}, \frac{\sigma_f}{\rho g h}, C_B, L/B \right]$$

$$\frac{N}{\rho g B L h^2} = f \left[\frac{r}{\sqrt{g/h}}, \frac{\sigma_f}{\rho g h}, C_B, L/B \right]$$

(Refer to opposite page for nomenclature)

The dimensional version of the derivative coefficients (Y_V , Y_r , N_V , N_r) required to compute the turning radius and stability criteria in a simulation exercise are obtained as follows:

$$Y_V = V_V \star \frac{\rho w g B h^2}{\sqrt{g h}}$$

$$N_V = N_V \star \frac{\rho w g B L h^2}{\sqrt{g h}}$$

$$Y_r = Y_r \star \frac{\rho w g B h^2}{\sqrt{g/h}}$$

$$N_r = N_r \star \frac{\rho w g B L h^2}{\sqrt{g/h}}$$

Y_v^* , N_v^* , Y_r^* , N_r^* are nondimensional force and moment slopes to be measured at $v/\sqrt{gh} = 0$ and the multiplication factors appearing in the above equations are distortion ratios. These distortion ratios are computed from a given ship's beam, length, ice thickness, gravity constant, and water density. These ratios will be the same for both the model and for the full-scale ship.

Source of Derivative Coefficients

Notation for the Type of Test

S_β Static Drift Angle Test
 Drift Angle β

R_ℓ Rotating Arm Test
 Arm Length ℓ , Drift Angle $\beta = 0^\circ$

$R_{\ell,\beta}$ Rotating Arm Test
 Arm Length ℓ , Drift Angle β

X - Equation

X_u X_u from theory [3]

X_u, X_{uu}, X_{uuu} ... From the Relation of Propeller Thrust and Ice Resistance as a Function of Speed.

X_{vv} From S_β

X_{rr} From $R_{\ell, 0}$

$X_{\delta\delta}$ Obtained from semi-empirical model

X_{vr} Considered to be negligible

$X_{v\delta}$ Included in $X_{\delta\delta}$

$X_{r\delta}$ Included in $X_{\delta\delta}$

$X_\star$ From S_β

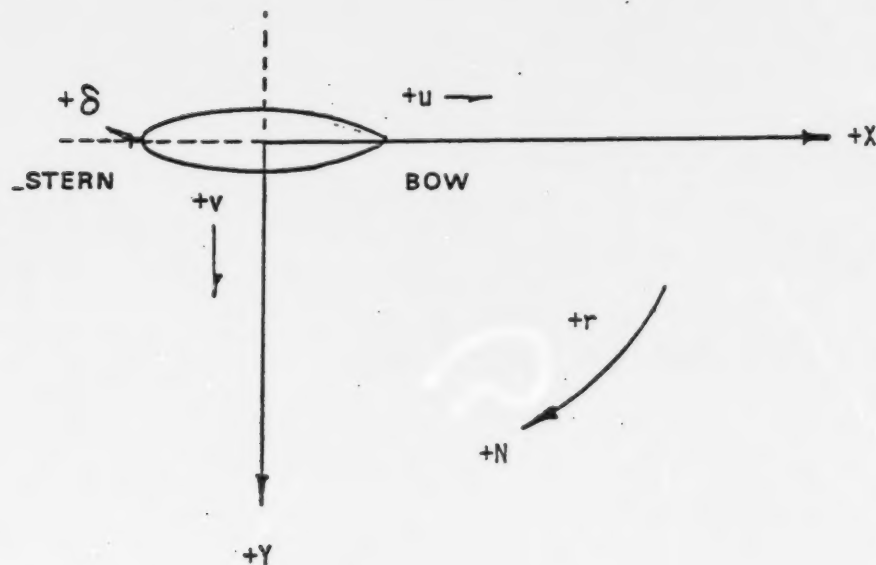
Y - Equation

Y_v [4]
 Y_r [4]
 Y_v, Y_{vv} From S_β
 Y_{vrr} Considered to be negligible
 $Y_{v\delta\delta}$ Considered to be negligible
 Y_r From $R_{\ell,0}$
 Y_{rrr} Considered to be negligible
 Y_{rvv} From $R_{\ell,\beta}$
 $Y_{r\delta\delta}$ Considered to be negligible
 Y_ϵ Empirically determined [4]
 $Y_{\delta\delta\delta}$ Considered to be negligible
 $Y_{\delta rr}$ Considered to be negligible
 $Y_{\delta vv}$ Considered to be negligible
 $Y_{\delta u}$ Considered to be negligible
 $Y_{vr\delta}$ Considered to be negligible
 Y_* Zero for symmetrical hull
 Y_u, Y_{uu} Considered to be negligible

N - Equation

N_v From theory and experiments [4]
 N_r From theory and experiments [4]
 N_v, N_{vv} From S_β
 N_{vrr} Considered to be negligible
 $N_{v\delta\delta}$ Considered to be negligible

COORDINATE DEFINITION FOR MANOEUVRING



NOMENCLATURE

g	Gravity constant
ρ_i	Ice Density
ρ_w	Water Density
h	Ice thickness
σ_f	Ice flexural strength
$\sigma_1, \sigma_2, \sigma_3$	Roots of stability equation
B	Beam of a ship
L	Length of a ship
C_B	Block Coefficient
R	Turning radius
V	Velocity of origin of body axes relative to fluid
u_1	Velocity in initial equilibrium
Δu	$u - u_1$
X_*, Y_*, N_*	Initial X , Y , and N at speed u_1

N_v	Typical static moment derivative; derivative of a moment component with respect to a velocity component $\partial N/\partial v$
N_{vrr}	Typical third partial derivative; partial derivative of a moment with respect to a velocity component and to an angular velocity component $\partial^3 N/\partial v \partial r^2$
$N_{\dot{v}}$	Typical moment of inertia coefficient; derivative of a moment component with respect to an acceleration component $\partial N/\partial \dot{v}$
m	Mass of body
r	Angular velocities of yaw
$\dot{r}$	Angular accelerations of yaw
$t, \Delta t$	Time and time interval, respectively
V	Velocity of origin of body axes relative to fluid
u, v	Longitudinal and transverse components of the velocity of the origin of body axes relative to fluid
$\dot{u}, \dot{v}$	Longitudinal and transverse components of the acceleration of the origin of body axes relative to fluid
X, Y	Longitudinal and lateral components of hydrodynamic force on body
Y_r	Typical rotary force derivative; derivative of a force component with respect to an angular velocity component $\partial Y/\partial r$
$Y_{r\delta\delta}$	Typical third partial derivative; partial derivative of a force with respect to an angular velocity component and to a rudder deflection $\partial^3 Y/\partial r \partial \delta^2$
$Y_{\dot{r}}$	Typical inertia coefficient; derivative of a force component with respect to an angular acceleration component $\partial Y/\partial \dot{r}$
x, y	Body axes fixed in ship, x and y positive forward, and starboard respectively. Origin of axes system not necessarily at center of gravity
x_G, y_G	Coordinates of center of mass relative to body axes
β	Angle of drift
δ	Angular displacement of a control surface, normally the rudder angle

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- [4] Icebreaker Model Manoeuvring Test Results, Arctec Canada Limited Report #15E, October 1973.
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APPENDIX C

MATHEMATICAL MANOEUVRING MODEL

- C.1 BASIC ASSUMPTIONS AND OVERVIEW OF MODEL
- C.2 BOW SIDE FORCE FROM BOW GEOMETRY
- C.3 FORCE AND MOMENT BALANCE
- C.4 ADAPTATION OF MATHEMATICAL MODEL TO USCGC POLAR STAR
- C.5 PROGRAMS USER INSTRUCTIONS
- C.6 SOURCE CODE LISTING

C.1 BASIC ASSUMPTIONS AND OVERVIEW OF MODEL:

1. Hydrodynamic forces have been neglected.

By neglecting the hydrodynamic forces, the total midbody side force is assumed to be due to ice only. At high ship speed, however, the hydrodynamic forces could be significant. The predicted turning radius would be therefore higher than expected, since the frictional side force component during turning would be reduced.

2. Total ice resistance ahead is assumed to be equal to the force acting on the bow in the direction of motion.

The predicted force acting on the bow in the opposite direction of motion is slightly higher since the frictional force components acting along the ship side and bottom have been neglected. However, the effect on the predicted turning radius is believed to be small since the bow angle of attack from which the turning radius is derived is a function of the ratio of the asymmetric bow side force when turning and the bow side force when moving ahead.

3. Ship bow is represented by simple geometry (See Figures and notes).

The mean half waterline angle could be slightly underestimated depending on the ship bow design. If this is the case, the predicted turning radius would be slightly higher than expected.

4. Ship centre of rotation is assumed to be at the centre of gravity.

If the ship centre of rotation is forward of the centre of gravity, the predicted turning radius would be slightly higher than expected. The converse is true if the centre of rotation happens to be aft of the centre of gravity.

5. The asymmetric bow side ice resistance is proportional to the difference in the volume of ice broken by the bow.

From assumption 5, the effect on the predicted turning radius is believed to be small for the same reason given in 2.

6. At the steady state, the ship is assumed to turn about a fixed centre of the turning circle.

From assumption 6, the effect on the predicted turning radius is similar to that given for assumption No. 4.

7. The midbody side force is assumed to be trapezoidally (2:1) distributed over the effective parallel midbody.

The predicted turning radius would definitely be underestimated if the midbody side force is acting further aft than the model is assuming.

The converse is also true, i.e. the predicted turning radius would be overestimated if the midbody side force is acting nearer to the centre of gravity than the model is assuming.

C.2 BOW SIDE FORCE FROM BOW GEOMETRY

1.0 SHIP BOW GEOMETRY

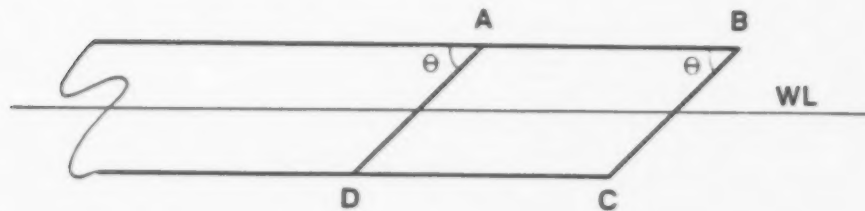
Ship's bow is represented by a simple geometry which is the combination of planes shown in Figure C.1 below:

Side planes of bow (ABCD, BA'D'C)

θ = buttock angle

α = half waterline angle

XZ PLANE



XY PLANE

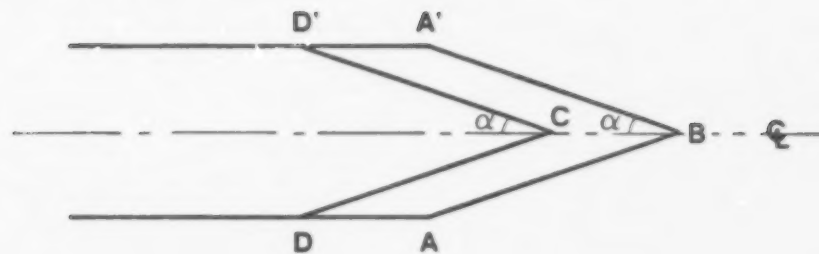
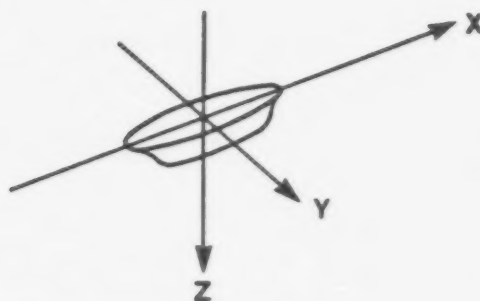


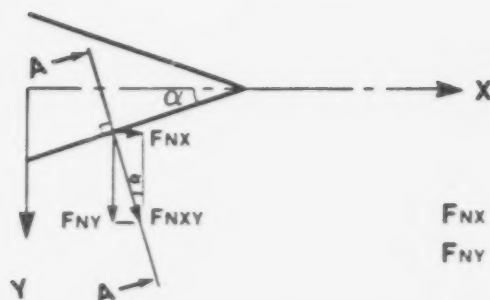
FIGURE C.1 SHIP'S BOW GEOMETRY



a) COORDINATES



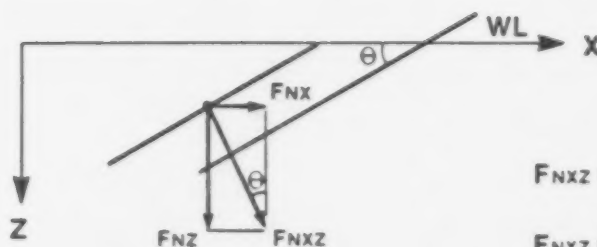
b) XY PLANE



$$F_{NX} = F_{NXY} \sin \alpha \quad (1)$$

$$F_{NY} = F_{NXY} \cos \alpha \quad (2)$$

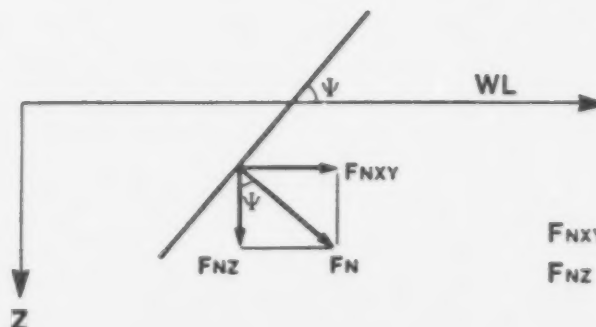
c) XZ PLANE



$$F_{NXZ} = \frac{F_{NZ}}{\cos \theta} \quad (3)$$

$$F_{NXZ} = \frac{F_{NX}}{\sin \theta} \quad (4)$$

d) A-A PLANE



$$F_{NXY} = F_N \sin \psi \quad (5)$$

$$F_{NZ} = F_N \cos \psi \quad (6)$$

FIGURE C.2 COMPONENTS OF NORMAL FORCE



2.0 COMPONENTS OF NORMAL FORCE

From equations (1) and (5):

$$F_{NX} = F_N \sin \psi \sin \alpha \quad (7)$$

From equations (2) and (5):

$$F_{NY} = F_N \sin \psi \cos \alpha \quad (8)$$

From equation (6):

$$F_{NZ} = F_N \cos \psi \quad (6)$$

From equation (5):

$$F_{NXY} = F_N \sin \psi \quad (5)$$

From equations (3) and (6):

$$F_{NXZ} = F_N \frac{\cos \psi}{\cos \theta} \quad (9)$$

From equations (4) and (7):

$$F_{NXZ} = F_N \frac{\sin \psi \sin \alpha}{\sin \theta} \quad (10)$$

From equations (9) and (10):

$$\frac{\cos \psi}{\cos \theta} = \frac{\sin \psi \sin \alpha}{\sin \theta} \quad (11)$$

$$\sin \alpha = \frac{\tan \theta}{\tan \psi} \quad (12)$$



$$\psi = \tan^{-1} \frac{(\tan \theta)}{(\sin \alpha)} \quad (13)$$

Where ψ = Angle between the horizontal plane and the section perpendicular to the waterline as shown in Figure C.2.



3.0 COMPONENTS OF FRICTIONAL FORCE

For the purposes of this work the direction of frictional force is assumed to be in the direction of the ship waterline, as shown in Fig. C.3.

Using the expressions, $F_{\mu} = F_N \tan \beta$, (14)

where β is the friction angle between the hull of the ship and the ice. The relationship between the total force and its normal component is given by:

$$F_{TOT} = \frac{F_N}{\cos \beta} \quad (15)$$

XY PLANE, FRICTION IN DIRECTION OF WATERLINES

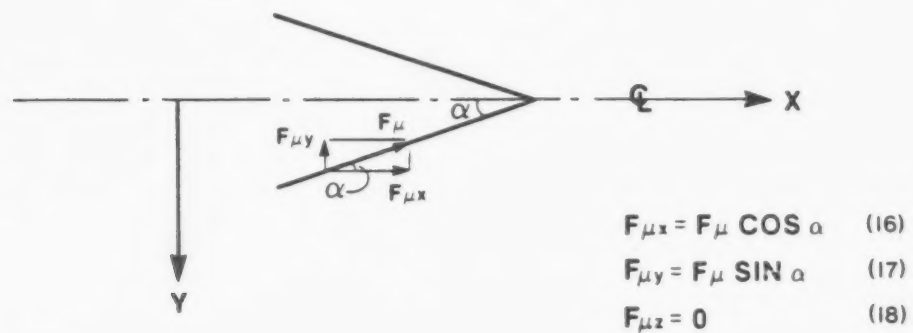


FIGURE C.3 COMPONENTS OF FRICTIONAL FORCE



4.0 COMPONENTS OF TOTAL FORCE

The direction cosines are developed for the total force as follows:

$$F_X = F_{NX} + F_{\mu X} \quad (19)$$

From equations (7) and (16):

$$F_X = F_N \sin \psi \sin \alpha + F_{\mu} \cos \alpha \quad (20)$$

From equation (14):

$$F_X = F_N \sin \psi \sin \alpha + F_N \tan \beta \cos \alpha \quad (21)$$

$$Q' = \frac{F_X}{F_{TOT}} \quad (22)$$

From equations (21) and (15):

$$Q' = \frac{F_N \sin \psi \sin \alpha + F_N \tan \beta \cos \alpha}{F_N / \cos \beta} \quad (23)$$

$$Q' = \cos \beta (\sin \psi \sin \alpha + \tan \beta \cos \alpha) \quad (24)$$

$$F_Y = F_{NY} - F_{\mu Y} \quad (25)$$

From equations (8), (14), (17):

$$F_Y = F_N \sin \psi \cos \alpha - F_N \tan \beta \sin \alpha \quad (26)$$

$$M' = \frac{F_Y}{F_{TOT}} \quad (27)$$

From equations (26) and (15):



$$M' = \frac{F_N \sin \psi \cos \alpha - F_N \tan \beta \sin \alpha}{F_N / \cos \beta} \quad (28)$$

$$M' = \cos \beta (\sin \psi \cos \alpha - \tan \beta \sin \alpha) \quad (29)$$

$$F_Z = F_{NZ} + F_{\mu Z} \quad (30)$$

From equations (6) and (18):

$$F_Z = F_N \cos \psi + 0$$

$$F_Z = F_N \cos \psi \quad (31)$$

$$n' = \frac{F_Z}{F_{TOTAL}} \quad (32)$$

$$n' = \frac{F_N \cos \psi}{F_N / \cos \beta} = \cos \psi \cos \beta \quad (33)$$



From equations (22) and (27):

$$F_y = \frac{F_x M'}{l'} \quad (34)$$

$$F_y = \frac{R_{ICE} M'}{2 l'} \quad (35)$$

Where:

R_{ICE} = Total ice resistance when moving straight ahead.

Substituting for M' and l' in equation (35):

$$F_y = \frac{R_{ICE}}{2} \frac{\sin \psi - \mu \tan \alpha}{\sin \psi \tan \alpha + \mu} \quad (36)$$

XY PLANE

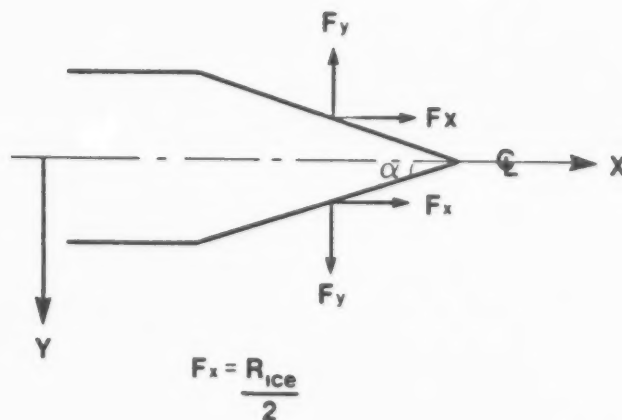


FIGURE C.4 COMPONENTS OF TOTAL FORCE



5.0 SYMMETRIC BOW SIDE FORCE

Consider the ship moving straight ahead with velocity, V m/s as shown in Fig. C.5.

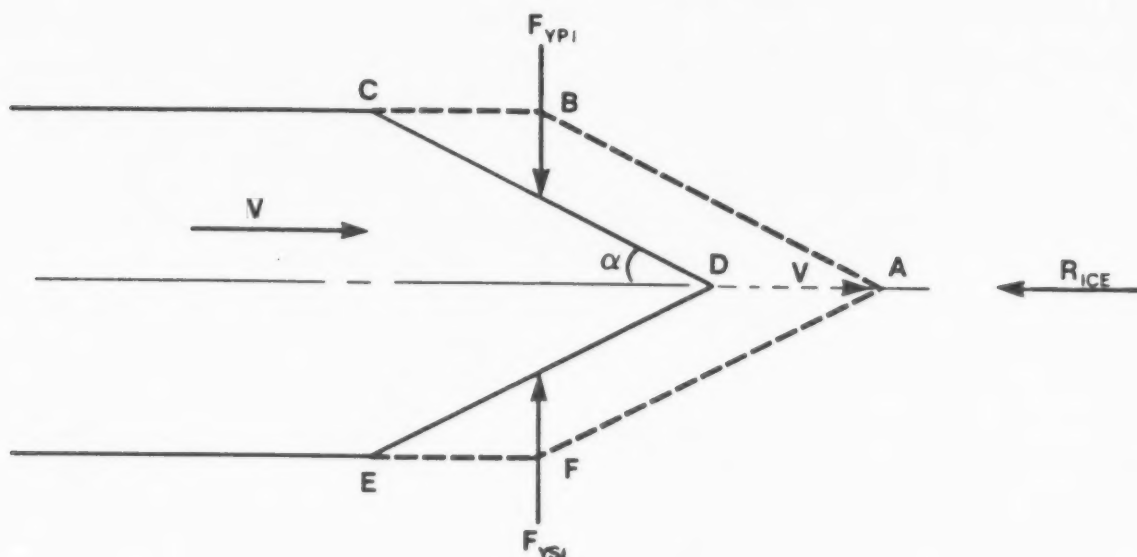


FIGURE C.5 SYMMETRIC BOW SIDE FORCES

From equation (35):

$$\text{Symmetric Bow Side Force } F_{YS1} = F_{YPI} = \frac{R_{ICE}}{2} \times \frac{m'}{l'} \quad (35)$$

Where

$$l' = \cos \beta (\sin \psi \sin \alpha + \tan \beta \cos \alpha)$$

$$m' = \cos \beta (\sin \psi \cos \alpha - \tan \beta \sin \alpha)$$

$$\alpha = \text{Mean half waterline angle}$$

$$\beta = \text{Friction angle} = \tan^{-1} \mu$$

$$\psi = \text{Angle between the horizontal plane and the section perpendicular to the waterline as shown in Figure C.2}$$



Volume of Ice Broken per unit time (s) on one side of bow, eg. starboard side, when moving straight ahead is given by:

$$\begin{aligned}\text{Volume ADEF from Fig. C.5} &= DE \sin \alpha H V \\ &= K V\end{aligned}\tag{37}$$

Where $K = \text{constant} = DE \sin \alpha H$



6.0 ASYMMETRIC BOW SIDE FORCE

Consider ship turning to starboard with velocity, V_t m/s as shown in Fig. C.6

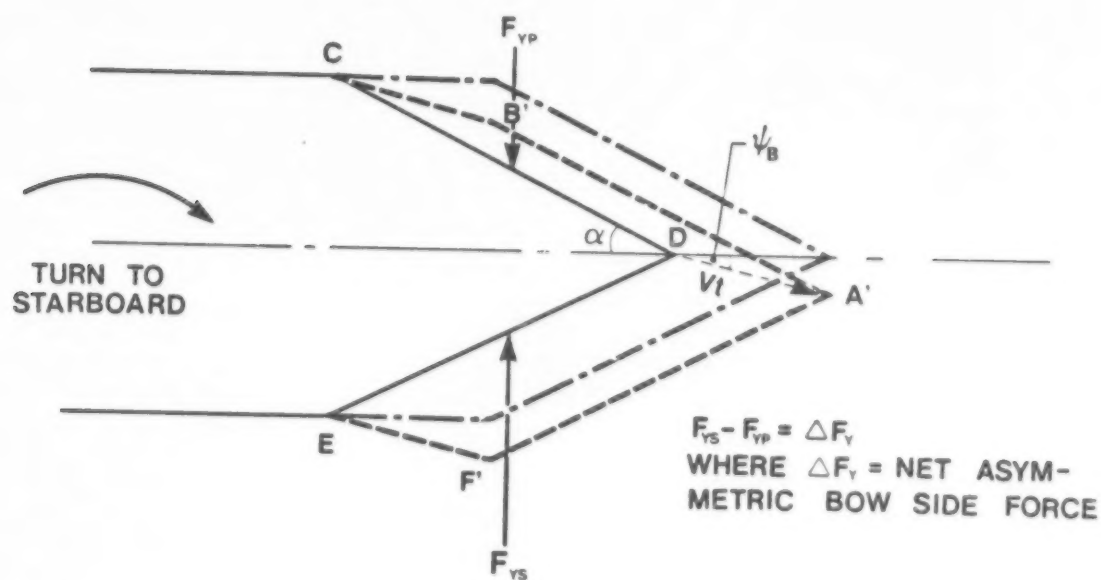


FIGURE C.6 ASYMMETRIC BOW SIDE FORCES

Net Asymmetric Bow Side Force,

$$\Delta F_y = F_{ys} - F_{yp} \quad (38)$$

$$\text{Volume } A'DEF' = V_t \cos(90 - \alpha - \psi_B) DE H \quad (39)$$

$$\text{Volume } A'B'CD = V_t \cos(90 - \alpha + \psi_B) DE H \quad (40)$$



$$\begin{aligned}
 \text{Volume (A'DEF' - A'B'CD)} &= V_t DE H [\cos (90 - \alpha - \psi_B) \\
 &\quad - \cos (90 - \alpha + \psi_B)] \\
 &= V_t DE H 2 \sin \psi_B \cos \alpha \\
 &= Cr V DE H 2 \sin \psi_B \cos \alpha
 \end{aligned} \tag{41}$$

Where:

V = speed straight ahead.
 V_t = speed during turn = $Cr \cdot V$
 Cr = speed reduction factor
 ψ_B = bow angle of attack as shown in Figure C.7

Assuming the asymmetric bow side ice resistance is proportional to the difference in the volume of ice broken per unit time.

$$\Delta F_Y = K_1 Cr V DE H 2 \sin \psi_B \cos \alpha \tag{42}$$

Where K_1 = Constant

Similarly, in a theoretical case where the net asymmetric bow force is assumed to be F_{YS} , then the resultant difference in volume of ice broken would be $DE \sin \alpha H V$.

Therefore,

$$F_{YS} = K_1 DE \sin \alpha H V \tag{43}$$

$$\begin{aligned}
 \frac{\Delta F_Y}{F_{YS}} &= \frac{K_1 Cr V DE H 2 \sin \psi_B \cos \alpha}{K_1 DE \sin \alpha H V} \\
 &= \frac{2 Cr \sin \psi_B \cos \alpha}{\sin \alpha}
 \end{aligned} \tag{44}$$

$$\begin{aligned}
 \frac{\Delta F_Y}{F_{YS}} &= \frac{2 Cr \sin \psi_B}{\tan \alpha} \\
 &= \frac{2 Cr \sin \psi_B}{\tan \alpha}
 \end{aligned} \tag{45}$$



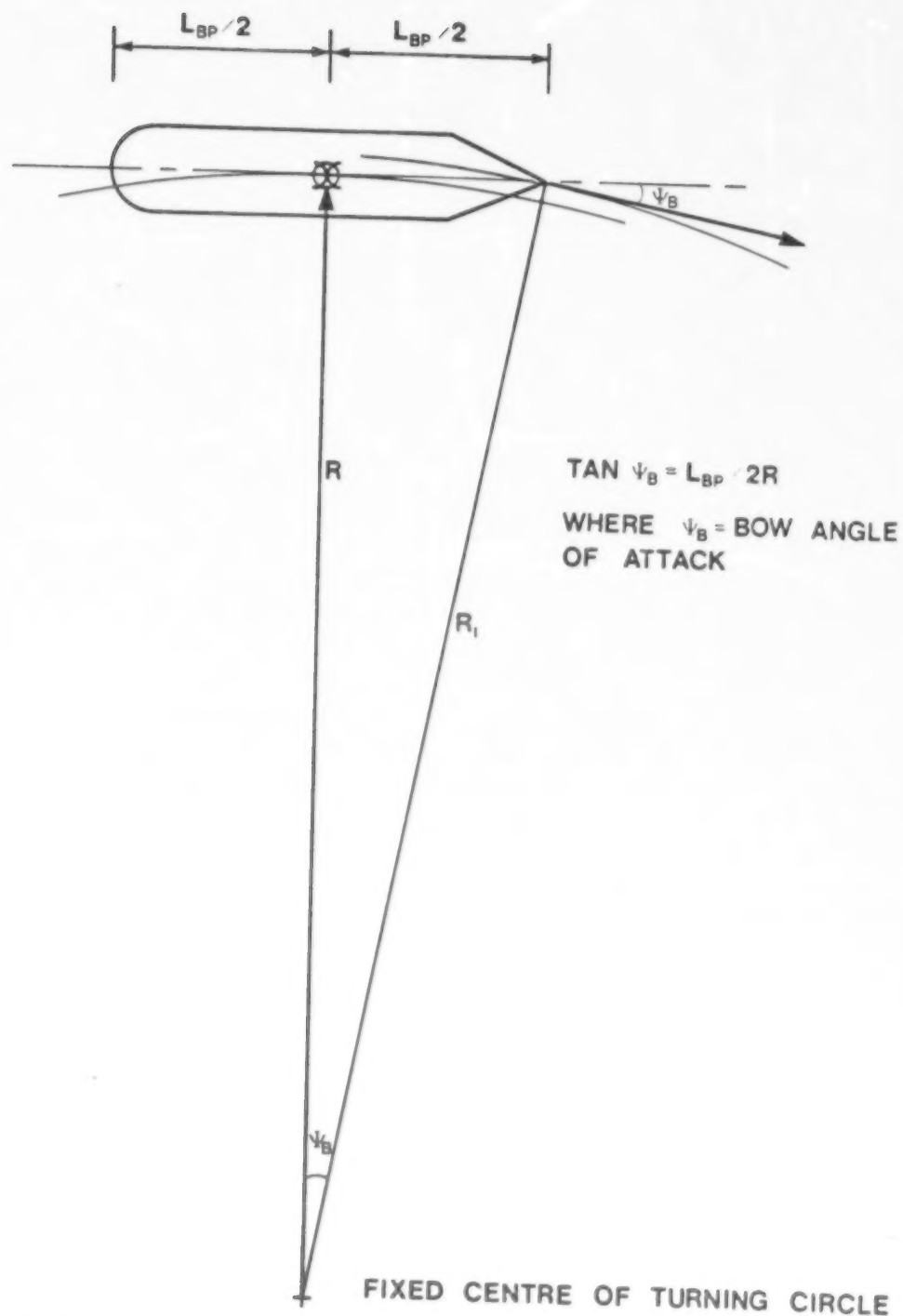


FIGURE C.7 BOW ANGLE OF ATTACK



C.3 FORCE AND MOMENT BALANCE

1.0 INITIAL FORCE AND MOMENT BALANCE

Assuming the midbody side force is acting at the centre of gravity (C.G.) or at the midship if the location of the C.G. is not known and neglecting the midbody side force frictional component, as shown in Figure C.8 below, the force moment balance is given by:

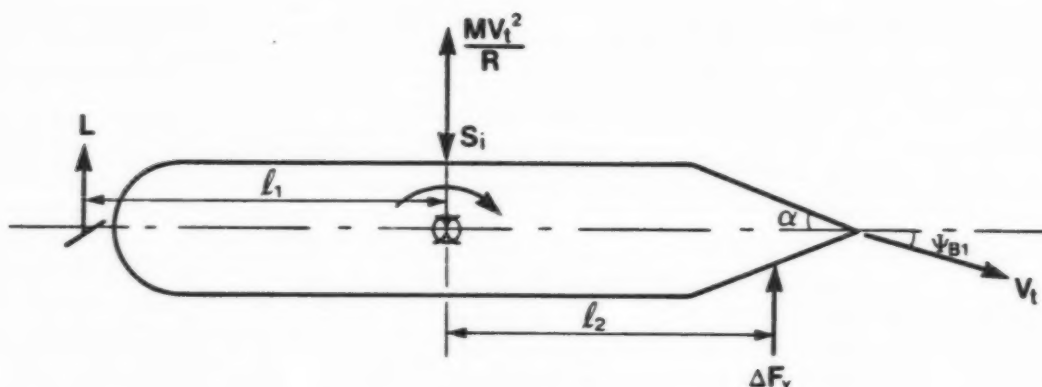


FIGURE C.8 INITIAL FORCE BALANCE

$$L l_1 - \Delta F_{Y1} l_2 = 0 \quad (1)$$

Where:

- L = Rudder lift force (N)
- ΔF_{Y1} = Asymmetric bow side force when turning (First estimate) (N)
- l_1 = Distance between centre of rudder and centre of gravity (M)
- l_2 = Distance between centre of ship bow and centre of gravity (M)



The first estimate of the asymmetric bow side force when turning, ΔF_{Y1} , is therefore equal to:

$$\Delta F_{Y1} = \frac{L \ell}{\frac{\ell}{2}} \quad (2)$$

Assuming the asymmetric bow side force is proportional to the difference in the volume of ice broken per unit time, the asymmetric bow side force is found to be equal to:

$$\Delta F_{Y1} = F_Y \frac{-2 Cr \sin \Psi}{\tan \alpha} \quad (3)$$

Where:

- F_Y = Symmetric bow side force when moving straight ahead (N)
- Cr = Speed reduction factor when turning
- Ψ_{B1} = Bow angle of attack (first estimate) (Degrees)
- α = Mean half waterline angle (Degrees)

From the simplified ship bow geometry and the assumption that the frictional force acts in the direction of the waterline, the symmetric bow side force was derived as follows:

$$F_Y = \frac{R_{ICE} M'}{2 \ell'} \quad (4)$$

Where:

- R_{ICE} = Total ice resistance when moving straight ahead (N)
- M' = $\cos \beta (\sin \Psi \cos \alpha - \tan \beta \sin \alpha)$
- ℓ' = $\cos \beta (\sin \Psi \sin \alpha + \tan \beta \cos \alpha)$
- $\tan \beta$ = μ = coefficient of friction
- Ψ = Mean angle between the horizontal plane and the section perpendicular to the waterline as shown in Figure C.2 (Degrees)
- = $\tan^{-1} \left(\frac{\tan \Theta}{(\sin \alpha)} \right)$



Θ = Mean bow buttock angle (Degrees)

The first estimate of the bow angle of attack can be determined from equation (3) as follows:

$$\Psi_{B1} = \frac{\sin^{-1} (\Delta F_{Y1} \tan \alpha)}{(2 Cr F_Y)} \quad (5)$$

The bow angle of attack is related to the steady state turning radius, as shown in Figure C.7, as follows:

$$\tan \Psi_{B1} = \frac{LBP}{2R_1} \quad (6)$$

Where:

R_1 = Turning radius (First estimate) (M)

LBP = Length between perpendiculars (M)

Therefore, the initial estimate of the turning radius, R_1 , which is usually underestimated, is given by:

$$R_1 = \frac{LBP}{2 \tan \Psi_{B1}} \quad (7)$$

Using the initial estimate of the turning radius and the asymmetric bow side force, the first estimate of the midbody side force can be calculated from the force balance as follows:

$$S_{11} = \frac{L + \frac{MV_t^2}{R_1} + \Delta F_{Y1}}{R_1} \quad (8)$$

Where:

S_{11} = Midbody side force (first estimate) (N)

M = Ship virtual mass ie. the mass of the vessel increased by the mass of the entrained water (Kg)

V_t = Ship speed during turning (M/S)



2.0 SUBSEQUENT ITERATIVE FORCE AND MOMENT BALANCE

Taking into account the first estimate of the midbody side force and its frictional component, as shown in Figure C.9 below, the second estimate of the asymmetric bow side force is given by:

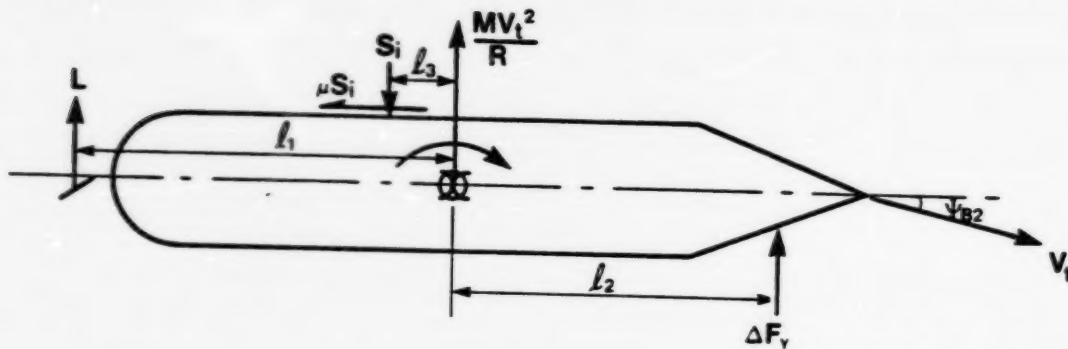


FIGURE C.9 FINAL FORCE BALANCE

$$\Delta F_{Y2} = \frac{L_1 - \mu S_{11} \frac{B}{2} - S_{11} L_3}{L_2} \quad (9)$$

Where:

B = Ship beam (M)

l_3 = Distance between the location of midbody side force to the centre of gravity (M)

The second estimate of the bow angle of attack is then calculated as follows:

$$\psi_{B2} = \frac{\sin^{-1} (\Delta F_{Y2} \tan \alpha)}{(2 Cr F_Y)} \quad (10)$$

The second estimate of the turning radius, R_2 , which is usually overestimated, is then given by:

$$R_2 = \frac{LBP}{2 \tan \psi_{B2}} \quad (11)$$

The iterative process is then repeated until the value of the turning radius converges and a solution is reached.



C.4 ADAPTATION OF MATHEMATICAL MODEL TO USCGC POLAR STAR

For the Polar Star, a 2:1 trapezoidal distribution of contact pressure was assumed since the forward end of the effective parallel midbody happens to be at the maximum waterline beam which was expected to experience considerable ice pressure (see attached figure: Polar Star - Effective Parallel Midbody)

The length of the bow entrance L_{bow} , used in the model is as follows:

$$L_{\text{bow}} = \frac{B}{2 \tan \alpha}$$

where B = Ship beam (m)

α = mean half angle of entrance of waterline (deg)

$$L_{\text{bow}} = \frac{23.8}{2 \tan 20.45^\circ} = 31.9 \text{ m}$$

The length of the parallel midbody is 37.58m.
The length of the stern "run" is therefore 37.8 metres.

Transverse Bow Force

The symmetric transverse bow force, F_Y , acting on a ship moving straight ahead was derived as equation (35)

$$F_Y = \frac{R_{\text{ice}} m'}{2 l'} \quad (35)$$

where R_{ice} = ice resistance when ship is moving ahead

$$R_{\text{ice}} = K_1 H^2 + K_2 HV \text{ (KN)} \quad (a)$$

H = ice thickness (m)

V = ship speed (m/s)

K_1 = constant

K_2 = constant

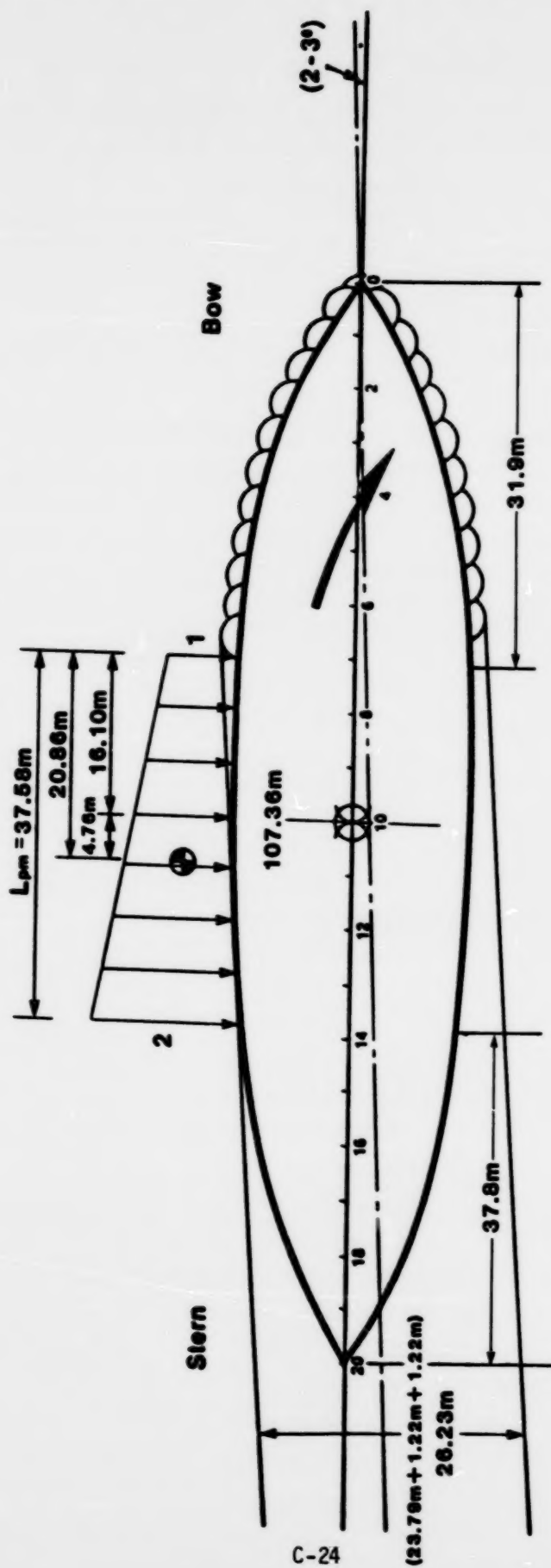
$$m' = \cos \beta (\sin \psi \cos \alpha - \tan \beta \sin \alpha) \quad (29)$$

$$l' = \cos \beta (\sin \psi \sin \alpha - \tan \beta \cos \alpha) \quad (24)$$

$$F_Y = K_3 (K_1 H^2 + K_2 HV)$$

where $K_3 = \frac{m'}{2 l'}$

Figure C.10
Polar Star - Effective Parallel Midbody



For unit time and a constant H

$$F_y = K_4 + K_5 (\text{vol}) \quad (b)$$

where

$$K_4 = K_3 K_1 H^2 = \text{constant}$$

$$K_5 = K_3 K_2 = \text{constant}$$

Vol = Volume of ice broken per unit time.

During the steady state turning process, both sides of the wedge-shaped bow are breaking ice. The main difference is that the inboard side of the bow is breaking more ice than the outboard side per unit time, causing a net transverse side force, as shown in Figure C6.

$$F_Y = F_{Ys2} - F_{Yp2} \quad (38)$$

From equation (b):

$$F_{Ys2} = K_4 + K_5 (\text{Vol}_s)$$

$$F_{Yp2} = K_4 + K_5 (\text{Vol}_p)$$

$$F_Y = K_5 (\text{Vol}_s - \text{Vol}_p) \quad (d)$$

The net ice forces on the bow in the transverse direction is therefore proportional to the difference in the volume of ice broken by the bow, as shown in equation (d)

For the Polar Star:

$$F_Y = K (Cr \ V \ DE \ H^2 \ \sin \psi_c \ \cos \alpha) \quad (42)$$

Assuming a theoretical case where there is a net asymmetric transverse bow force equal in magnitude to F_{Ys1} or F_{Yp1} , the resultant difference in volume of ice broken would then be

$DE \sin \alpha \ HV$

$$F_{Ys1} = F_{Yp1} = K (DE \sin \alpha \ HV) \quad (37)$$

From (37) and (42)

$$F_Y = F_{Ys1} \left(\frac{Cr \ \sin \psi_c \ 2}{\tan \alpha} \right) \quad (45)$$

It is agreed that the flare angles, buttock angles and waterline angles do influence the net transverse force acting on the bow. In

this simplified model, the volume of ice broken per unit time has assumed to be only dependent on the waterline angle and bow angle of attack. It is recommended that in the future development and refinement of the model, a conventional ship shaped bow should be used taking into account the flare and buttock angles.

C. 5 PROGRAM USER INSTRUCTIONS

MATHEMATICAL MANEUVERING MODEL "POLAR-FS"

NOTE: This program has been designed for use in the Hewlett-Packard HP 9816 computer. It is written in HP Extended Basic. Detailed information is available in the HP Operating and Procedure Manual.

The program must be supplied with the input data which consists of the ship particulars, ship performance in ice and propeller and rudder particulars. The inputs for the computer should be ready before the program is run.

For the program "POLAR-FS", the input data are those of the USCGC POLAR STAR, during the January 1985 full scale tests.

1. "Ship effective parallel midbody length " refers to the length of the ship midbody that is pressing against the ice edge during the steady state turning phase.
2. "Mean half angle of entrance of waterline" is the mean of the half angles of entrance of waterline at the designed draft and at two-third of the designed draft measured at $B/20$, $3B/20$, $5B/20$, $7B/20$ and $9B/20$ from the centreline. (B = Ship beam).
3. "Mean angle between waterline and bow buttock" is the mean of the angles measured between the waterlines at the designed draft and at two-third of the designed draft and the buttock lines at $B/20$, $3B/20$, $5B/20$, $7B/20$ and $9B/20$ from the centreline. (B = ship beam).



DEFINITIONS:

Type: means to enter from the keyboard the information exactly as shown or instructed.

press: means to use the stated function key.

CONT: means to press the CONT (continue) key.

PROGRAM EXECUTION STEPS:

- 1) Place the HP Basic 2.0 disc in the left hand disc drive and turn all machines on. The HP Basic 2.0 is loaded automatically, when completed remove the disc.
- 2) Place the HP extended Basic 2.1 disc in the left hand disc drive.
type LOAD BIN "AP2_1"
press EXEC
Remove the disc when HP extended Basic 2.1 is loaded.
- 3) Place the program disc in the left hand disc drive.
type LOAD "POLAR1M"
when loaded, press RUN
- 4) ENTER: SHAFT HORSEPOWER (SHP)
type the shaft horsepower of the ship and press CONT.
- 5) ENTER: ICE THICKNESS (M)
type the ice thickness required in metres and press CONT.
- 6) ENTER: SHIP SPEED AHEAD (M/SEC)
type the estimated ship speed ahead in m/s for the above power level and in the above ice thickness and press CONT.



- 7) ENTER: Thrust from center propeller during turn (kN)
type the measured thrust from center shaft.
- 8) ENTER: Thrust from port wing propeller during turn (kN)
type the measured thrust from port shaft.
- 9) ENTER: Thrust from starboard wing propeller during turn (kN)
type the measured thrust from starboard shaft.
- 10) ENTER: Turn to port or to starboard (P or S)?
type "P" for turn to port
type "S" for turn to starboard
- 11) ENTER: RUDDER ANGLE (Degrees)
type the rudder angle required in degrees and press CONT.
The program is then executed and the results are displayed on the screen
- 12) Do you want a hard copy of results (Y or N)?
type "Y" if you want a copy of results.
The results will then be printed on paper (see sample of output)
type "N" if you do not want a copy of results
- 13) Do you want to run another case (Y or N)?
type "Y" if you want to run another case.
type "N" if you do not want to run another case.



MATHEMATICAL MANOEUVRING MODEL

INPUT DATA SHEET

METRIC UNITS

DATE: 84.12.17
 USER NAME: Balji Menon
 NAME OF VESSEL: USCGC POLAR STAR

SHIP PARTICULARS:

SHIP WATERLINE LENGTH (M) = 107.3
 SHIP LENGTH BETWEEN PERPENDICULARS (M) = 107.3
 SHIP EFFECTIVE PARALLEL MIDBODY LENGTH (M) = 37.5
 SHIP BEAM AT WL (M) = 23.8
 SHIP DISPLACEMENT (TONNES) = 13405
 MEAN HALF ANGLE OF ENTRANCE OF WATERLINE (DEGREES) = 20.45
 MEAN ANGLE BETWEEN WATERLINE AND BOW BUTTOCK (DEGREES) = 20.85
 DISTANCE BETWEEN CENTRE OF RUDDER AND CENTRE OF GRAVITY (M) = 49.84
 DISTANCE BETWEEN CENTRE OF BOW AND CENTRE OF GRAVITY (M) = 37.7
 DISTANCE BETWEEN START OF MIDBODY FORWARD TO CENTRE OF GRAVITY (M) = 16.1
 DISTANCE BETWEEN MIDSHIP AND CENTRE OF GRAVITY (M) (+FWD, -AFT) = 0

SHIP PERFORMANCE:

TOTAL SHAFT HORSEPOWER (SHP)* = 60,000
 ICE THICKNESS (M)* = 1.5
 SHIP SPEED AHEAD (M/SEC)* = 3.0
 HULL-ICE FRICTION FACTOR = 0.08

PROPELLER AND RUDDER PARTICULARS:

PROPELLER DISK AREA (M²) = 17.35
 NUMBER OF RUDDERS = 1
 RUDDER AREA (M²) = 27.61
 RUDDER ANGLE (DEGREES)* = 30
 RUDDER ASPECT RATIO = 1.28

*VARIABLE INPUT

C.6. SOURCE CODE LISTING

```

10  I PROGRAM TO PREDICT SHIP TURNING DIAMETER IN LEVEL ICE
20  I PROGRAM NAME: "POLARIM"
30  I METRIC UNITS WERE USED IN THIS PROGRAM
40  I PROGRAM CREATED 84/11/20 BY KIN TUE-FEE
50  I PROGRAM UPDATED 84/12/17
60  OPTION BASE 1
70  DEG I ALL ANGLES ARE CALCULATED IN DEGREES
80  I DECLARE VARIABLES
90  INTEGER I,N
100 REAL Lvl,Lv2,Lv3,X1
110 REAL Ri,Ri1,Ri2,M,Ra,Ro
120 REAL H,Lwl,Lm,B,V,Us,Vt,Vt2,T,T1,Tcp,F,Cr,Tp,Td
130 REAL At,Ar,Ap,Ct,U,U1,C1,C11,C12,C13
140 REAL Psi,Alfa,F1,Be
150 REAL Psi1,Alfa1,Fil
160 REAL Li,M1,N1
170 REAL A1,B1,C1,C2,C3
180 REAL Lift,Lift1,Lift2
190 REAL Fs,Dfs(1:19),S(1:20),Ta(1:19),R(1:19)
200 I
210 Main: I
220 GOSUB Input_data
230 GOSUB Resistance
240 GOSUB Speed
250 GOSUB Thrust
260 GOSUB Lift
270 GOSUB Bow_force
280 GOSUB Force_balance
290 GOSUB Results
300 STOP
310 II
320 Input_data: I
330 I SHIP PARTICULARS:
340 I INPUT "ENTER: SHIP WATERLINE LENGTH (M)",Lwl
350 I INPUT "ENTER: SHIP LENGTH BETWEEN PERPENDICULARS (M)",Lbp
360 I INPUT "ENTER: SHIP EFFECTIVE PARALLEL MIDBODY LENGTH (M)",Lpm
370 I INPUT "ENTER: SHIP BEAM (M)",B
380 I INPUT "ENTER: SHIP DISPLACEMENT (TONNES)",M
390 I INPUT "ENTER: HALF ANGLE OF ENTRANCE OF WATERLINE (DEGREES)",Alfa
400 I INPUT "ENTER: ANGLE BETWEEN WATERLINE AND BOW BUTTOCK (DEGREES)",F1
410 I INPUT "ENTER: DISTANCE BETWEEN CENTRE OF RUDDER AND CENTRE OF GRAVITY (M)
",Lv1
420 I INPUT "ENTER: DISTANCE BETWEEN CENTRE OF BOW AND CENTRE OF GRAVITY (M)",L
v2
430 I INPUT "ENTER: DISTANCE BETWEEN START OF MIDBODY FORWARD TO CENTRE OF GRAV
ITY (M)",X1
431 I INPUT "ENTER: DISTANCE BETWEEN MIDSHIP AND CENTRE OF GRAVITY (M) (+ FWD,
- AFT)",X2

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440      I SHIP PERFORMANCE:
450      INPUT "ENTER: SHAFT HORSEPOWER (SHP)";Shp
460      INPUT "ENTER: ICE THICKNESS (M)";H
470      INPUT "ENTER: SHIP SPEED AHEAD (M/SEC)";U
480      INPUT "ENTER: LEVEL ICE RESISTANCE AHEAD (KN)";R11
490      INPUT "ENTER: THRUST FROM CENTER PROPELLER ONLY DURING TURN (KN)";Top
500      INPUT "ENTER: SHIP SPEED REDUCTION FACTOR DURING TURN";Cr
510      INPUT "ENTER: HULL-ICE FRICTION FACTOR";F
520      I PROPELLER AND RUDDER PARTICULARS:
530      INPUT "ENTER: PROPELLER DISK AREA (M^2)";Ap
540      INPUT "ENTER: NUMBER OF RUDDERS";Nu
550      INPUT "ENTER: RUDDER AREA (M^2)";At
560      INPUT "ENTER: RUDDER ANGLE (DEGREES)";Ra
570      INPUT "ENTER: RUDDER ASPECT RATIO";Ar
580      INPUT "IS RUDDER LOCATED BEHIND PROPELLER (Y OR N) ?";Q$
590      IF UPC$(Q$)="N" THEN INPUT "ENTER: ESTIMATED FLOW VELOCITY AT RUDDER (M/SE
C)";U
600      INPUT "ENTER: LIFT COEFFICIENT";Cl
610      "POLAR STAR" — CASE STUDY
620      Lwl=107.3
630      Lbp=107.3
640      Lpm=37.5
650      B=23.8
660      M=13405
670      F=.08
680      Lv1=49.84
690      Lv2=37.70
700      X1=16.10
701      X2=0
710      Nu=1
720      At=27.61
730      Ar=1.28
740      Ap=17.35
750      Alfa=20.45
760      Fi=20.85
770      RETURN
780 Resistance:      I
790      I LEVEL ICE RESISTANCE PREDICTIONS BASED ON FULL SCALE DATA (ARCTEC)
800      R12=921*H^2+348*H*U
810      I R12=LEVEL ICE RESISTANCE IN KILONEWTONS (KN)
820      R1=R12
830      IF R11>0 THEN R1=R11
840      RETURN
850 Speed:      I
860      I SPEED DURING TURN IS REDUCED BY THE REDUCTION FACTOR,
      I DEPENDING ON RUDDER ANGLE AND SHIP DESIGN
870      Cr1=.93+.06*H
880      Cr2=.945+.02*H
890      IF Ra>10 AND Ra<40 THEN Cr=Cr2-(Cr2-Cr1)/30*(Ra-10)
900      IF Ra=40 THEN Cr=Cr1
910      IF Ra=10 THEN Cr=Cr2
920      IF Cr>1 THEN Cr=1
930      IF U=0 THEN GOTO 470
940      Ut=Cr*U
950      RETURN

```



```

960 Thrust: !
970 ! RELATIONSHIP BETWEEN PROPELLER THRUST AND SHIP SPEED
980 ! BASED ON ARCTEC APPROX. EQUATIONS
990 C1=3.4
1000 C2=.73
1010 C3=.053
1020 Vt2=Vt/.5144
1030 Ro=C1*Vt2+C2*Vt2^2+C3*Vt2^3
1040 IF Shp=60000 THEN Tp=4500-176*Vt2
1050 IF Shp=40000 THEN Tp=3200-129*Vt2
1060 IF Shp=18000 THEN Tp=1870-102*Vt2
1070 Td=.06+.01*Vt2
1080 T=(Tp+Ro)/(1-Td)
1090 RETURN
1100 Lift: !
1110 ! RUDDER LIFT FORCE CALCULATED FROM HYDRODYNAMIC RUDDER CALCULATIONS
1120 IF Shp=60000 THEN
1130 Lift1=1.957056E-2*Ra^3-1.667447E+0*Ra^2+6.386715E+1*Ra-2.266238E+2
1140 Lift2=1.994413E-2*Ra^3-1.644334E+0*Ra^2+5.752942E+1*Ra-1.582954E+2
1150 IF H>.9 AND H<1.8 THEN Lift=(Lift2-Lift1)/.9*(H-.9)+Lift1
1160 IF H=.9 THEN Lift=Lift1
1170 IF H=1.8 THEN Lift=Lift2
1180 END IF
1190 IF Shp=40000 THEN
1200 Lift1=1.795476E-2*Ra^3-1.501252E+0*Ra^2+5.320676E+1*Ra-2.276119E+2
1210 Lift2=1.242338E-2*Ra^3-1.034061E+0*Ra^2+3.840357E+1*Ra-8.967316E+1
1220 IF H>.6 AND H<1.5 THEN Lift=(Lift2-Lift1)/.9*(H-.6)+Lift1
1230 IF H=.6 THEN Lift=Lift1
1240 IF H=1.5 THEN Lift=Lift2
1250 END IF
1260 IF Shp=18000 THEN
1270 Lift1=1.027059E-2*Ra^3-8.512798E-1*Ra^2+3.013821E+1*Ra-1.153839E+2
1280 Lift2=8.375453E-3*Ra^3-6.947296E-1*Ra^2+2.541601E+1*Ra-7.035873E+1
1290 IF H>.6 AND H<.9 THEN Lift=(Lift2-Lift1)/.3*(H-.6)+Lift1
1300 IF H=.6 THEN Lift=Lift1
1310 IF H=.9 THEN Lift=Lift2
1320 END IF
1330 RETURN
1340 Bow_force: !
1350 ! RELATIONSHIP BETWEEN BOW ANGLES
1360 Psi=ATN(TAN(Fi)/SIN(Alfa))
1370 Be=ATN(F)
1380 ! CALCULATE DIRECTION COSINES
1390 L1=COS(Be)*(SIN(Psi)*SIN(Alfa)+TAN(Be)*COS(Alfa))
1400 M1=COS(Be)*(SIN(Psi)*COS(Alfa)-TAN(Be)*SIN(Alfa))
1410 N1=COS(Psi)*COS(Be)
1420 ! CALCULATE APPARENT BOW ANGLES
1430 Alfa1=ATN(L1/M1)
1440 Fi1=ATN(L1/N1)
1450 Psi1=ATN(TAN(Fi1)/SIN(Alfa1))
1460 ! CALCULATION OF SHIP BOW SIDE FORCES
1470 Fy=(R1*M1)/2*L1)
1480 RETURN

```



```

1490 Force_balance: |
1500 | LEVER FOR MIDBODY SIDE FORCE ABOUT MIDSHIP
1510 | CALCULATE ASYMMETRIC BOW SIDE FORCE DURING TURN
1520 | CALCULATE BOW ANGLE OF ATTACK
1530 | CALCULATE SHIP TURNING RADIUS
1540 | Lv3=0 | MIDBODY SIDE FORCE IS ASSUMED TO ACT AT MIDSHIP
1550 | Lv3=.5*Lpm-X1 | MIDBODY SIDE FORCE IS UNIFORMLY DISTRIBUTED OVER
1560 | PARALLEL MIDBODY
1570 | Lv3=.555*Lpm-X1 | MIDBODY SIDE FORCE IS DISTRIBUTED TRAPEZOIDALLY
1580 | (2:1) OVER PARALLEL MIDBODY
1590 | Lv3=.667*Lpm-X1 | MIDBODY SIDE FORCE IS DISTRIBUTED TRIANGULARLY
1600 | OVER PARALLEL MIDBODY
1610 | Lv3=.78*Lpm-X1 | MIDBODY SIDE FORCE IS DISTRIBUTED ELLIPSOIDALLY
1620 | OVER PARALLEL MIDBODY
1630 FOR I=1 TO 19
1640 IF I=1 THEN
1650 Dfs(I)=Lift*Lv1/Lv2
1660 ELSE
1670 Dfs(I)=(Lift*Lv1-F*S(I)*B/2-Lv3*S(I))/Lv2
1680 END IF
1690 Temp=Dfs(I)*TAN(Alfa)/(2*Cr*Fs)
1700 IF ABS(Temp)>1 THEN
1710 DISP "TEMP =",Temp
1720 SEEP
1730 GOTO 1780
1740 ELSE
1750 Ta(I)=ASN(Temp)
1760 R(I)=(Lbp-(X2))/(2*TAN(Ta(I)))
1770 S(I+1)=Lift+(M*Ut^2)/R(I)+Dfs(I)
1780 END IF
1790 NEXT I
1800 RETURN
1810 Results: |
1820 PRINT TAB(10);"MATHEMATICAL MODEL FOR PREDICTING SHIP TURNING RADIUS IN L
EVEL ICE"
1830 PRINT
1840 PRINT " INPUT DATA: 'POLAR STAR' "
1850 PRINT
1860 PRINT " SHIP PARTICULARS:"
1870 PRINT
1880 PRINT " SHIP WATERLINE LENGTH (M) = ";Lwl
1890 PRINT " SHIP LENGTH BETWEEN PERPENDICULARS (M) = ";Lbp
1900 PRINT " SHIP EFFECTIVE PARALLEL MIDBODY LENGTH (M) = ";Lpm
1910 PRINT " SHIP BEAM (M) = ";B
1920 PRINT " SHIP DISPLACEMENT (TONNES) = ";M
1930 PRINT " HALF ANGLE OF ENTRANCE OF WATERLINE (DEGREES) = ";Alfa
1940 PRINT " ANGLE BETWEEN WATERLINE AND BOW BUTTOCK (DEGREES) = ";F1
1950 PRINT " DISTANCE BETWEEN CENTRE OF RUDDER AND CENTRE OF GRAVITY (M) = ";L
v1
1960 PRINT " DISTANCE BETWEEN CENTRE OF BOW AND CENTRE OF GRAVITY (M) = ";Lv2
1970 PRINT " DISTANCE BETWEEN START OF MIDBODY FWD TO CENTRE OF GRAVITY (M) =
";X1
1971 PRINT " DISTANCE BETWEEN MIDSHIP AND CENTRE OF GRAVITY (M) (+ FWD, - AFT)
= ";X2

```

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1980 PRINT
1990 PRINT " SHIP PERFORMANCE:"
2000 PRINT
2010 PRINT " SHAFT HORSEPOWER (SHP) = ":Shp
2020 PRINT " ICE THICKNESS (M) = ":H
2030 PRINT " SHIP SPEED AHEAD (M/SEC) = ":U
2040 PRINT " LEVEL ICE RESISTANCE AHEAD (KN) = ":R11
2050 PRINT " THRUST FROM CENTER PROPELLER ONLY DURING TURN (KN) = ":TcP
2060 PRINT " HULL-ICE FRICTION FACTOR = ":F
2070 PRINT
2080 PRINT " PROPELLER AND RUDDER PARTICULARS:"
2090 PRINT
2100 PRINT " PROPELLER DISK AREA (M^2) = ":Ap
2110 PRINT " NUMBER OF RUDDERS = ":Nu
2120 PRINT " RUDDER AREA (M^2) = ":At
2130 PRINT " RUDDER ANGLE (DEGREES) = ":Ra
2140 PRINT " RUDDER ASPECT RATIO = ":Ar
2150 PRINT
2160 PRINT " CALCULATED VALUES:"
2170 PRINT
2180 PRINT USING "43A,DDDDDD": " PREDICTED LEVEL ICE RESISTANCE AHEAD (KN)= ":R
12
2190 PRINT USING "51A,DDDDDD": " PREDICTED TOTAL PROPELLER THRUST DURING TURN (
KN)= ":T
2200 PRINT USING "31A,.DD": " SHIP SPEED REDUCTION FACTOR = ":Cr
2210 PRINT USING "33A,DD.DD": " SHIP SPEED DURING TURN (M/SEC)= ":Ut
2220 PRINT USING "20A,D.DDD": " LIFT COEFFICIENT = ":Cl
2230 PRINT USING "24A,DDDDDD": " TOTAL RUDDER LIFT (KN)= ":Lift
2240 PRINT USING "42A,DD.DD": " CALCULATED VELOCITY AT RUDDER (M/SEC) = ":U
2250 PRINT USING "58A,DDD.D": " LEVER FOR MIDBODY SIDE FORCE ABOUT CENTRE OF GR
AVITY (M)= ":Lv3
2260 PRINT USING "65A,DD.D": " ANGLE BETWEEN HOR. PLANE AND SECTION PERP. TO WA
TERLINE (DEG)= ":Psi
2270 PRINT " DIRECTION COSINES : "
2290 PRINT USING "4A,D.DDD": "L1 = ":L1
2290 PRINT USING "4A,D.DDD": "M1 = ":M1
2300 PRINT USING "4A,D.DDD": "N1 = ":N1
2310 PRINT USING "48A,DDDDDD": " SHIP BOW SIDE FORCE DURING AHEAD MOTION (KN)= "
:Fb
2311 PRINT USING "48A,DDDDDD": " ASYMMETRIC BOW SIDE FORCE DURING TURNING (KN)= "
:Ofb(19)
2312 PRINT USING "47A,DDDDDD": " SHIP MIDBODY SIDE FORCE DURING TURNING (KN)= ":S
(19)
2313 PRINT USING "33A,DD.DD": " BOW ANGLE OF ATTACK (DEGREES)= ":Ta(19)
2320 PRINT
2390 PRINT
2400 PRINT "IMAGE 10X,DDDDDDDDDD,5X,DDD.DD,5X,DDDDDDDD,5X,DDDDDDDDDD"
2410 PRINT "TAB(13)=:Ofb(19) TAB(16)=:Ta(19) TAB(19)=:S(19) TAB(22)=:Fb(19) TAB(25)=:L(19)

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2420 | FOR I=1 TO 5
2430 |   PRINT USING 2400;Dfs(I);Ta(I);R(I);S(I)
2440 | NEXT I
2450 | PRINT
2460 | PRINT " PREDICTED TURNING RADIUS:"
2470 | PRINT " -----"
2471 | PRINT
2480 | PRINT " ICE THICKNESS (M) = ";H
2490 | PRINT USING "22A,DDDDDD";" TURNING RADIUS (M) = ";R(19)
2500 | PRINT USING "41A,DD.D";" TURNING RADIUS PER SHIP LENGTH (LBP) = ";R(19)/L
bp
2510 | INPUT "DO YOU WANT TO RUN ANOTHER CASE (Y OR N) ? ",Q1$
2520 | IF Q1$="Y" THEN GOTO Main
2530 | RETURN
2540 | END

```

APPENDIX D
FULL SCALE TURNING CIRCLES OF USCGC POLAR STAR

LIST OF FIGURES

TESTS IN ICE:

PAGE #

TESTS 1 - 5 STEADY "S" TURNS IN LEVEL ICE

D3 - D39

TESTS IN OPEN WATER:

STEADY TURN 30° STBD RUDDER	- TEST 01	D40
STEADY TURN 30° PORT RUDDER	- TEST 02	D41
STEADY TURN 30° STBD RUDDER	- TEST 03	D42
STEADY TURN 30° PORT RUDDER	- TEST 04	D43
10° - 10° ZIG ZAG	- TEST 05	D44
20° - 20° ZIG ZAG	- TEST 06	D45
CRASH STOP ZERO RUDDER	- TEST 07	D46

USCSC POLAR STAR MANEUVERING TRIALS-ANTARCTICA

TEST: SECTOR No. 1

27 Feb 1985

START SCAN = 57

STOP SCAN = 75

AVERAGE SHIP SPEED	4.8	knots
AVERAGE RUDDER ANGLE	-10.3	deg (+ve=port)

AVERAGE PORT THRUST	80142	lbs
AVERAGE CENTRE THRUST	53269	lbs
AVERAGE STBD THRUST	74234	lbs

TOTAL THRUST	207564	lbs
--------------	--------	-----

CHANGE IN HEADING	5.850	deg
ELAPSED TIME	90.0	sec
ARC LENGTH	250.1	meters
RECKONED SPEED	5.4	knots

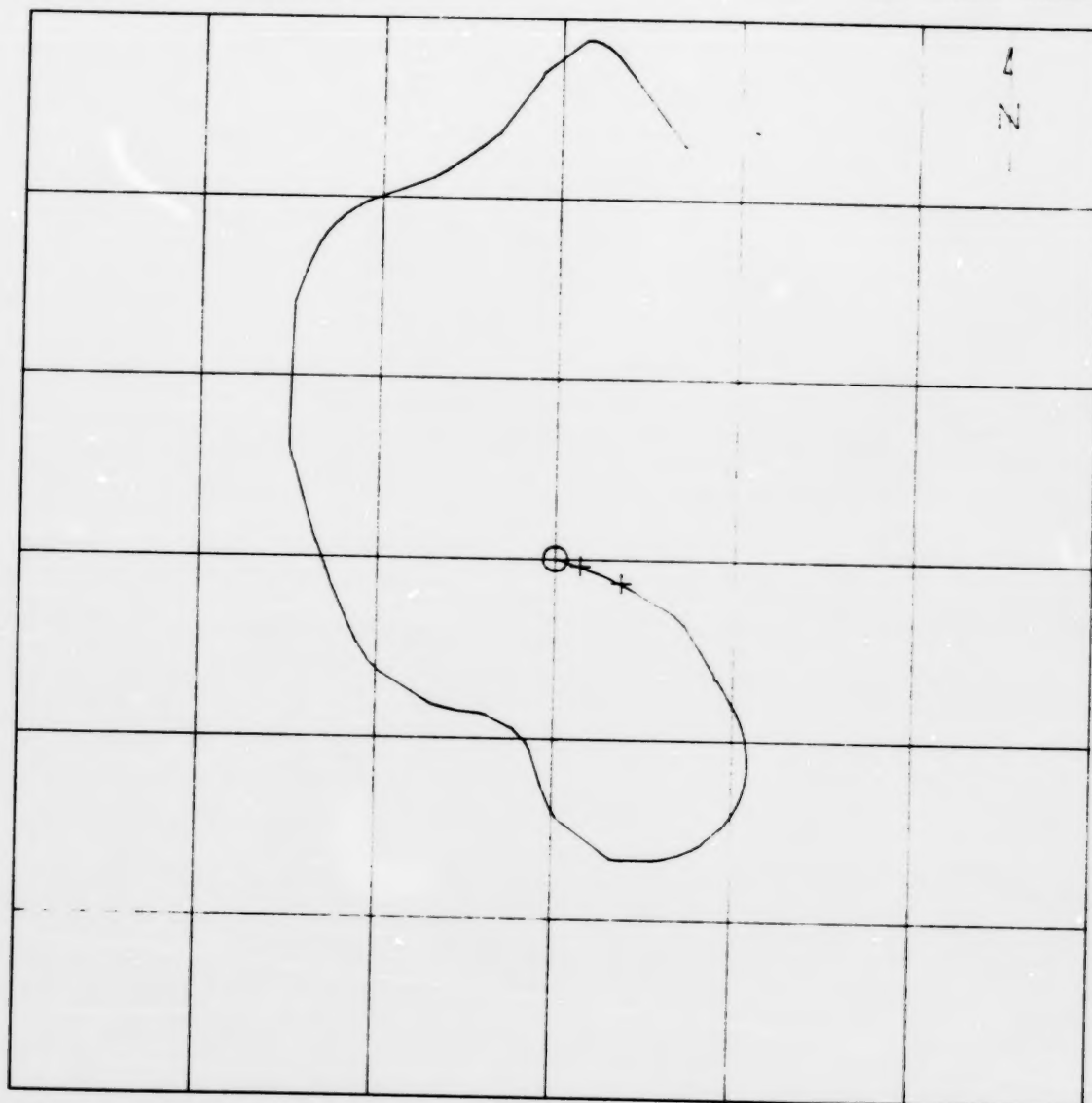
AVERAGE RATE OF HEADING	.0650	deg/sec
TIME TO TURN 180 DEG	46.15	min

TURNING CIRCLE RADIUS	2450	meters
TURN CIRCLE RADIUS/LBP	22.83	
TURN CIRCLE RADIUS/WLL	23.82	
TURN CIRCLE DIAMETER	5359	yds

USCGC POLAR STAR
JANUARY 1985 MANOEUVERING TESTS

TEST 1 SECTOR 1

21 Jan 1985



GRID SPACING 1000 meters

START LOCATION
SECTOR DELIMITER

○
+

USCGC POLAR STAR MANEUVERING TRIALS-ANTARCTICA

TEST1 SECTOR No. 2

27 Feb 1985

START SCAN = 138

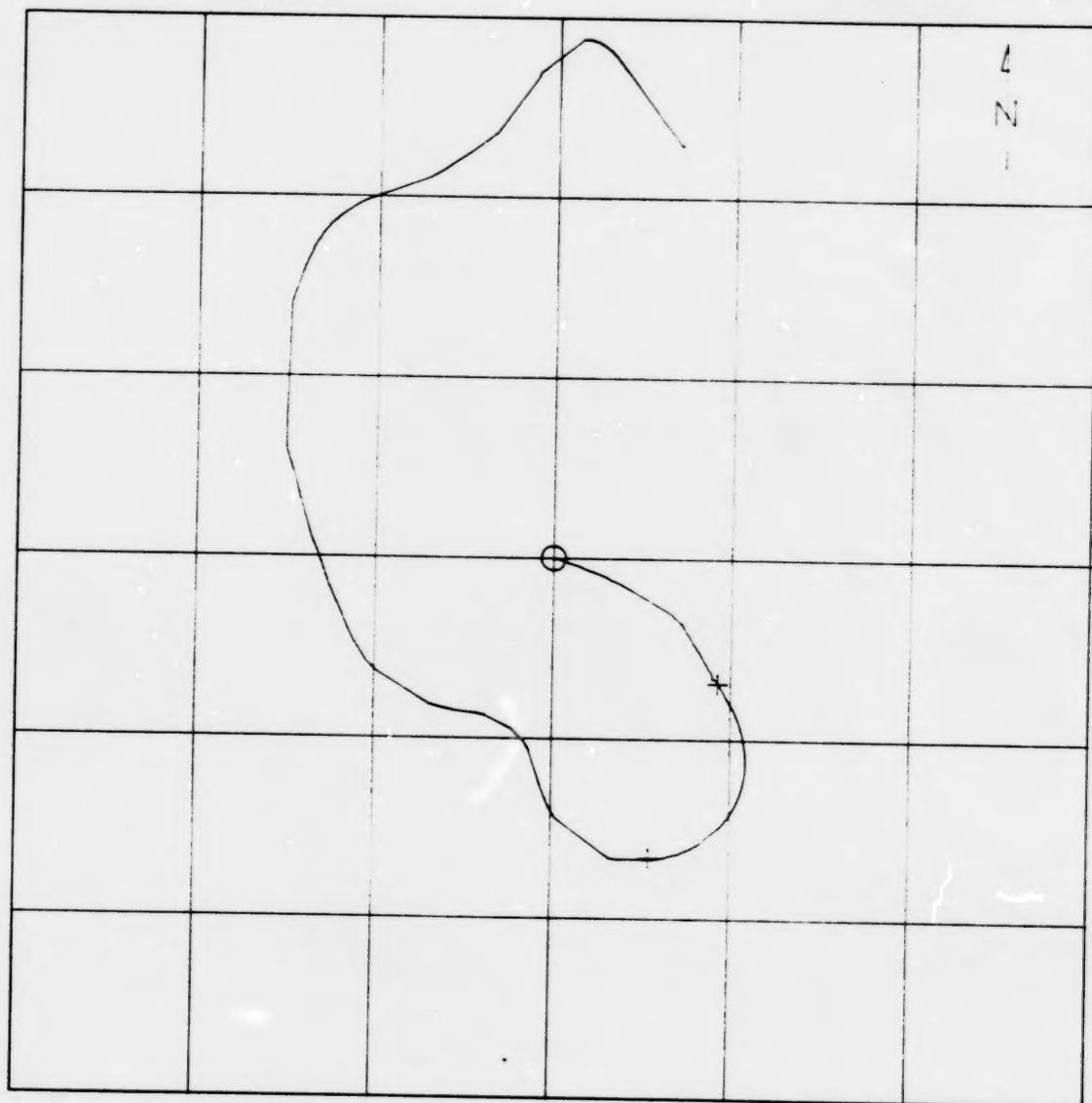
STOP SCAN = 617

AVERAGE SHIP SPEED	4.3	knots
AVERAGE RUDDER ANGLE	-30.1	deg (+ve=port)
AVERAGE PORT THRUST	90883	lbs
AVERAGE CENTRE THRUST	96850	lbs
AVERAGE STBD THRUST	90973	lbs
TOTAL THRUST	248606	lbs
CHANGE IN HEADING	116.100	deg
ELAPSED TIME	529.5	sec
ARC LENGTH	1337.3	meters
RECKONED SPEED	4.9	knots
AVERAGE RATE OF HEADING	.2193	deg/sec
TIME TO TURN 180 DEG	13.66	min
TURNING CIRCLE RADIUS	650	meters
TURN CIRCLE RADIUS/LBP	6.15	
TURN CIRCLE RADIUS/WLL	6.42	
TURN CIRCLE DIAMETER	1444	yds

USCGC POLAR STAR
JANUARY 1985 MANOEUVERING TESTS

TFST 1 SECTOR 2

21 Jan 1985



GRID SPACING 1000 meters

START LOCATION
SECTOR DELIMITER

○
+

USCGC POLAR STAR MANEUVERING TRIALS-ANTARCTICA

TEST1 SECTOR No. 3

27 Feb 1985

START SCAN = 924

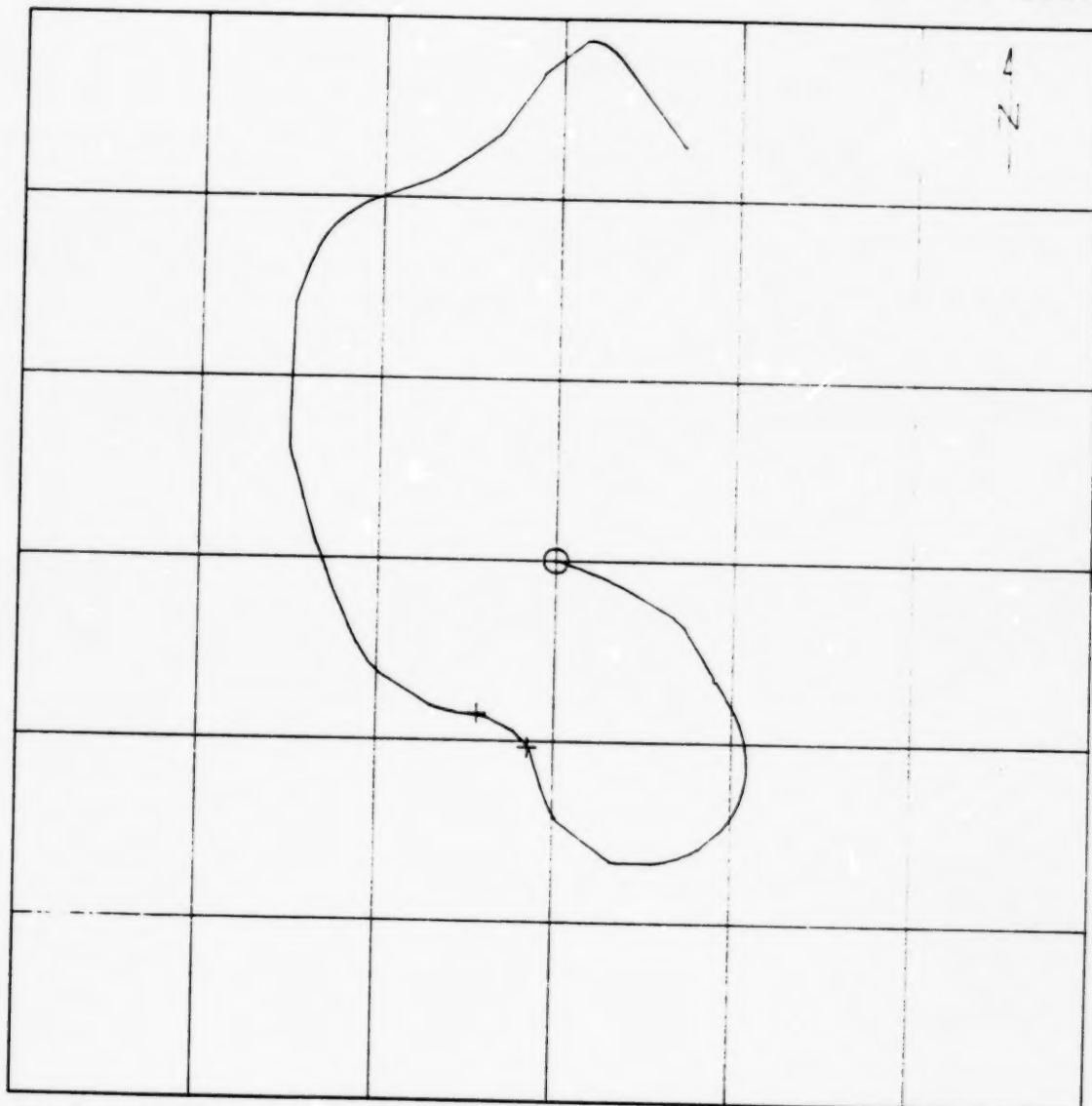
STOP SCAN = 1077

AVERAGE SHIP SPEED	4.2	knots
AVERAGE RUDDER ANGLE	19.0	deg (+ve=port)
AVERAGE PORT THRUST	95181	lbs
AVERAGE CENTRE THRUST	115701	lbs
AVERAGE STBD THRUST	58463	lbs
TOTAL THRUST	269345	lbs
CHANGE IN HEADING	48.870	deg
ELAPSED TIME	157.6	sec
ARC LENGTH	367.3	meters
RECKONED SPEED	4.5	knots
AVERAGE RATE OF HEADING	.3100	deg/sec
TIME TO TURN 180 DEG	9.68	min
TURNING CIRCLE RADIUS	431	meters
TURN CIRCLE RADIUS/LBP	4.01	
TURN CIRCLE RADIUS/WLL	4.19	
TURN CIRCLE DIAMETER	942	yds

USCGC POLAR STAR
JANUARY 1985 MANOEUVERING TESTS

TEST 1 SECTOR 3

21 Jan 1985



GRID SPACING 1000 meters

START LOCATION ○
SECTOR DELIMITER +

USCGC POLAR STAR MANEUVERING TRIALS-ANTARCTICA

TEST2 SECTOR No. 1

27 Feb 1985

START SCAN = 919

STOP SCAN = 1365

AVERAGE SHIP SPEED	4.5	knots
AVERAGE RUDDER ANGLE	-17.2	deg (+ve=port)

AVERAGE PORT THRUST	9110	lbs
AVERAGE CENTRE THRUST	124843	lbs
AVERAGE STBD THRUST	74994	lbs

TOTAL THRUST	208947	lbs
--------------	--------	-----

CHANGE IN HEADING	83.160	deg
ELAPSED TIME	457.1	sec
ARC LENGTH	1255.4	meters
RECKONED SPEED	5.3	knots

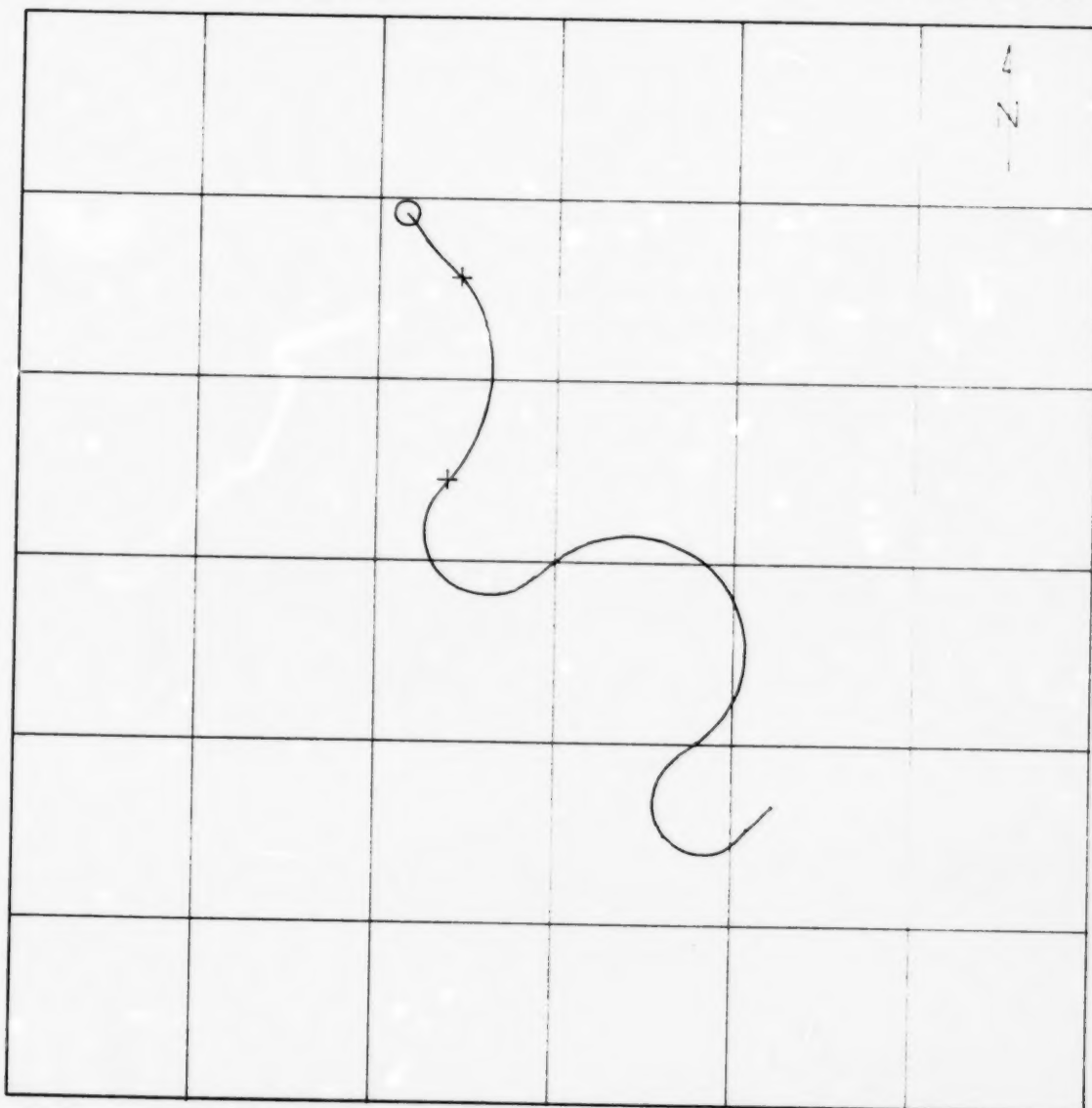
AVERAGE RATE OF HEADING	.1819	deg/sec
TIME TO TURN 180 DEG	16.49	min

TURNING CIRCLE RADIUS	865	meters
TURN CIRCLE RADIUS/LBP	8.06	
TURN CIRCLE RADIUS/WLL	8.41	
TURN CIRCLE DIAMETER	1892	yds

USCGC POLAR STAR
JANUARY 1985 MANOEUVERING TESTS

TEST 2 SECTOR 1

22 Jan 1985



GRID SPACING 1000 meters

START LOCATION ○
SECTOR DELIMITER +

USCGC POLAR STAR MANEUVERING TRIALS-ANTARCTICA

TEST2 SECTOR No. 2

27 Feb 1985

START SCAN = 1424

STOP SCAN = 1898

AVERAGE SHIP SPEED	3.4	knots
AVERAGE RUDDER ANGLE	19.4	deg (+ve=port)

AVERAGE PORT THRUST	32634	lbs
AVERAGE CENTRE THRUST	110827	lbs
AVERAGE STD THRUST	58303	lbs

TOTAL THRUST	201964	lbs
--------------	--------	-----

CHANGE IN HEADING	149.950	deg
ELAPSED TIME	476.0	sec
ARC LENGTH	998.0	meters
RECKONED SPEED	4.1	knots

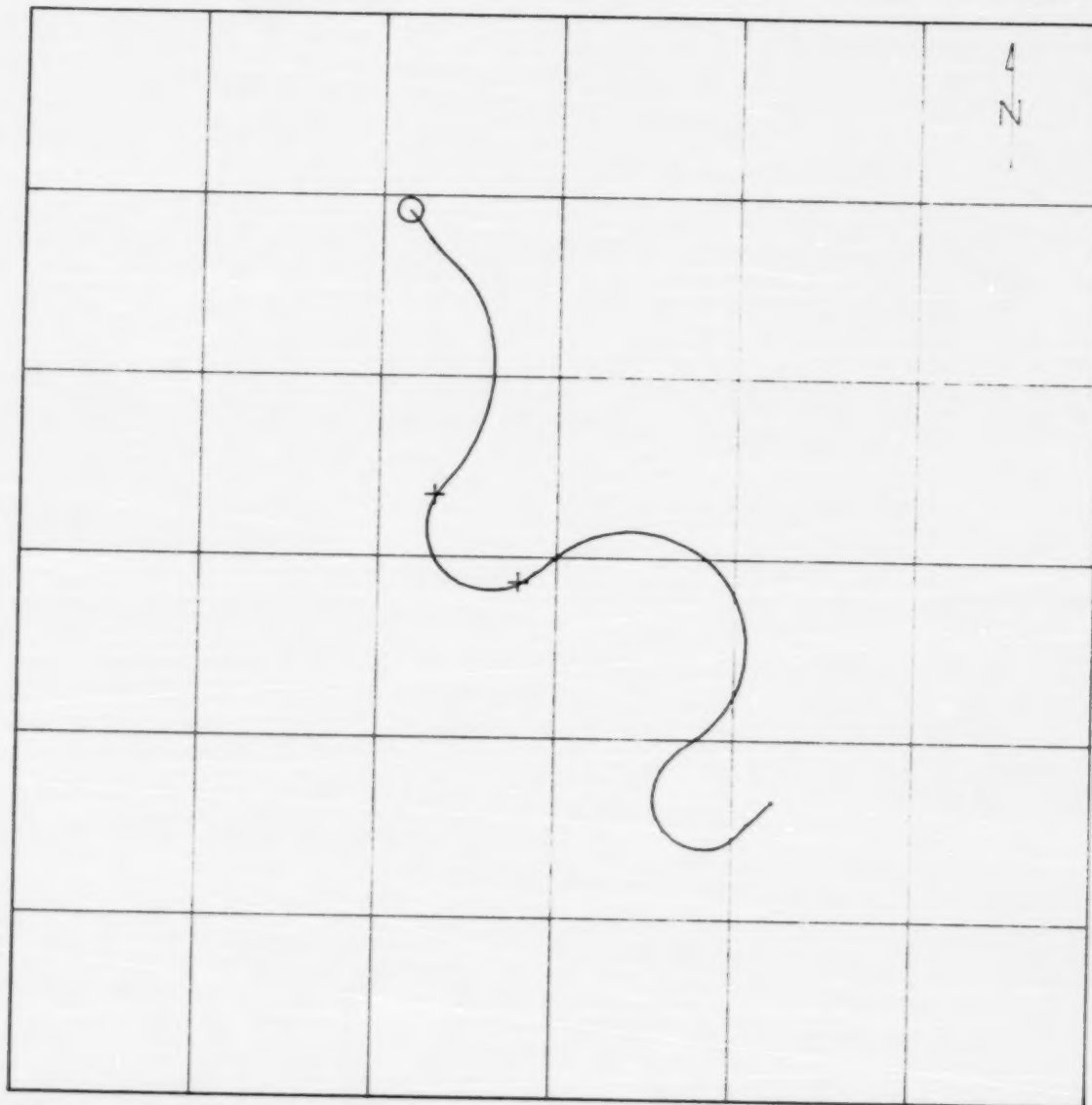
AVERAGE RATE OF HEADING	.3148	deg/sec
TIME TO TURN 180 DEG	9.63	min

TURNING CIRCLE RADIUS	382	meters
TURN CIRCLE RADIUS/LBP	3.56	
TURN CIRCLE RADIUS/WLL	3.71	
TURN CIRCLE DIAMETER	835	yds

USCGC POLAR STAR
JANUARY 1985 MANOEUVERING TESTS

TEST 2 SECTOR 2

22 Jan 1985



GRID SPACING 1000 meters

START LOCATION ○
SECTOR DELIMITER +

USCGC POLAR STAR MANEUVERING TRIALS-ANTARCTICA

TEST2 SECTOR No. 3

27 Feb 1985

START SCAN = 1997

STOP SCAN = 2986

AVERAGE SHIP SPEED	3.5	knots
AVERAGE RUDDER ANGLE	-22.4	deg (+ve=port)

AVERAGE PORT THRUST	17846	lbs
AVERAGE CENTRE THRUST	126670	lbs
AVERAGE STBD THRUST	85513	lbs

TOTAL THRUST	230029	lbs
--------------	--------	-----

CHANGE IN HEADING	178.830	deg
ELAPSED TIME	1023.7	sec
ARC LENGTH	2319.2	meters
RECKONED SPEED	4.4	knots

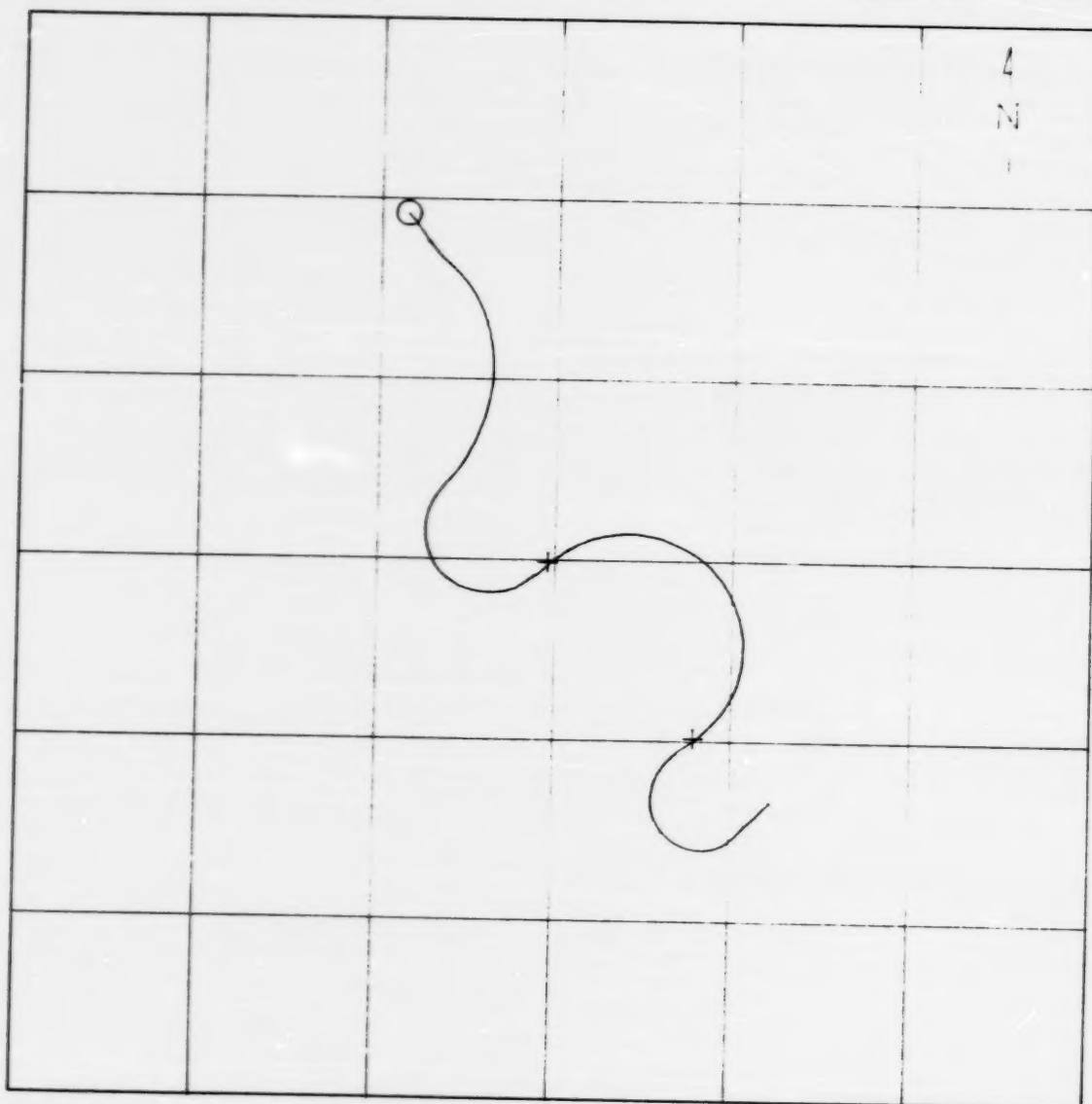
AVERAGE RATE OF HEADING	.1747	deg/sec
TIME TO TURN 180 DEG	17.17	min

TURNING CIRCLE RADIUS	743	meters
TURN CIRCLE RADIUS/LBP	6.92	
TURN CIRCLE RADIUS/WLL	7.22	
TURN CIRCLE DIAMETER	1625	yds

USCGC POLAR STAR
JANUARY 1985 MANOEUVERING TESTS

TEST 2 SECTOR 3

22 Jan 1985



GRID SPACING 1000 meters

START LOCATION ○
SECTOR DELIMITER +

USCGC POLAR STAR MANEUVERING TRIALS-ANTARCTICA

TEST2 SECTOR No. 4

27 Feb 1985

START SCAN = 3113

STOP SCAN = 3650

AVERAGE SHIP SPEED	2.9	knots
AVERAGE RUDDER ANGLE	25.2	deg (+ve=port)

AVERAGE PORT THRUST	41470	lbs
AVERAGE CENTRE THRUST	114294	lbs
AVERAGE STBD THRUST	71198	lbs

TOTAL THRUST	226962	lbs
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CHANGE IN HEADING	176.760	deg
ELAPSED TIME	558.0	sec
ARC LENGTH	1013.2	meters
RECKONED SPEED	3.5	knots

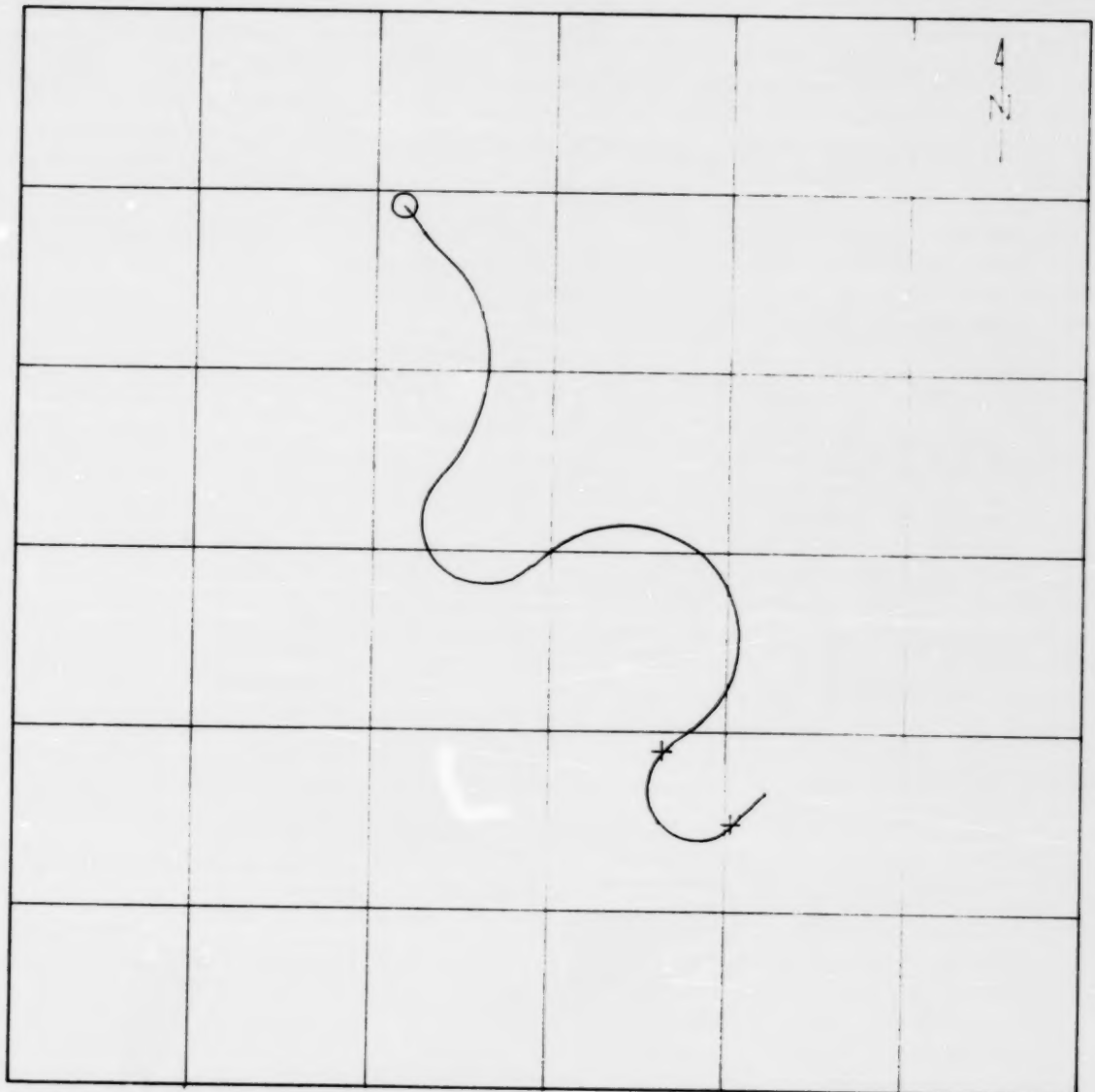
AVERAGE RATE OF HEADING	.3168	deg/sec
TIME TO TURN 180 DEG	9.47	min

TURNING CIRCLE RADIUS	329	meters
TURN CIRCLE RADIUS/LBP	3.06	
TURN CIRCLE RADIUS/WLL	3.19	
TURN CIRCLE DIAMETER	718	yds

USCGC POLAR STAR
JANUARY 1985 MANOEUVERING TESTS

TEST 2 SECTOR 4

22 Jan 1985



GRID SPACING 1000 meters

START LOCATION ○
SECTOR DELIMITER +

USCGC POLAR STAR MANEUVERING TRIALS-ANTARCTICA

TEST3 SECTOR No. 1

27 Feb 1985

START SCAN = 470

STOP SCAN = 742

AVERAGE SHIP SPEED	3.2	knots
AVERAGE RUDDER ANGLE	17.8	deg (+ve=port)

AVERAGE PORT THRUST	43278	lbs
AVERAGE CENTRE THRUST	79183	lbs
AVERAGE STBD THRUST	64272	lbs

TOTAL THRUST	186733	lbs
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CHANGE IN HEADING	84.330	deg
ELAPSED TIME	279.0	sec
ARC LENGTH	625.3	meters
RECKONED SPEED	4.4	knots

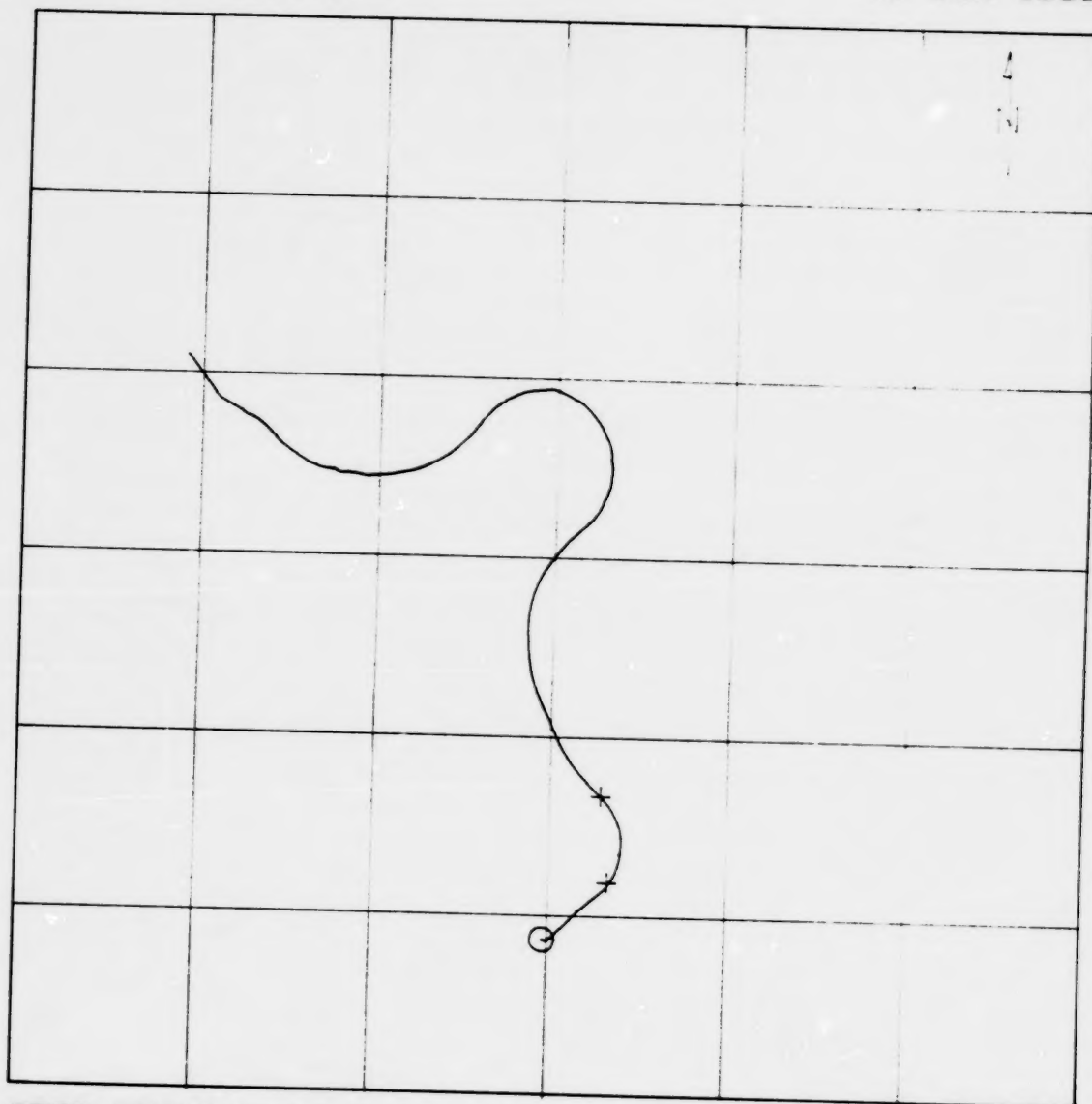
AVERAGE RATE OF HEADING	.3023	deg/sec
TIME TO TURN 180 DEG	9.93	min

TURNING CIRCLE RADIUS	425	meters
TURN CIRCLE RADIUS/LBP	3.96	
TURN CIRCLE RADIUS/WLL	4.13	
TURN CIRCLE DIAMETER	929	yds

USCGC POLAR STAR
JANUARY 1985 MANOEUVERING TESTS

TEST 3 SECTOR 1

22 Jan 1985



GRID SPACING 1000 meters

START LOCATION ○
SECTOR DELIMITER +

USCGC POLAR STAR MANEUVERING TRIALS-ANTARCTICA

TEST3 SECTOR No. 2

27 Feb 1985

START SCAN = 1271

STOP SCAN = 1655

AVERAGE SHIP SPEED	3.7	knots
AVERAGE RUDDER ANGLE	-27.0	deg (+ve=port)

AVERAGE PORT THRUST	25923	lbs
AVERAGE CENTRE THRUST	68291	lbs
AVERAGE STED THRUST	93741	lbs

TOTAL THRUST	187955	lbs
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CHANGE IN HEADING	59.940	deg
ELAPSED TIME	394.2	sec
ARC LENGTH	872.5	meters
RECKONED SPEED	4.3	knots

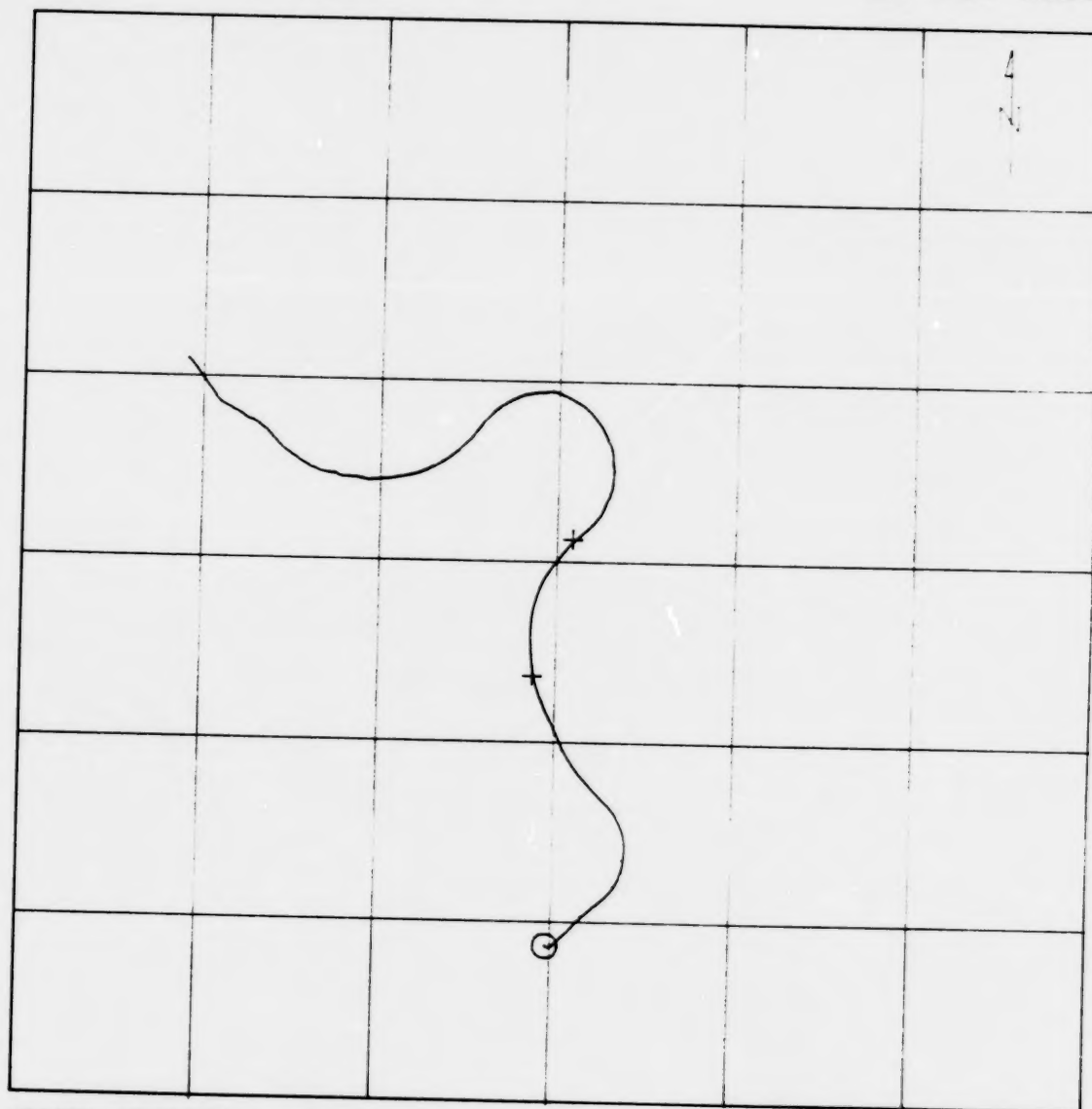
AVERAGE RATE OF HEADING	.1521	deg/sec
TIME TO TURN 180 DEG	19.73	min

TURNING CIRCLE RADIUS	834	meters
TURN CIRCLE RADIUS/LBP	7.77	
TURN CIRCLE RADIUS/WLL	8.11	
TURN CIRCLE DIAMETER	1824	yds

USCGC POLAR STAR
JANUARY 1985 MANOEUVERING TESTS

TEST 3 SECTOR 2

22 Jan 1985



GRID SPACING 1000 meters

START LOCATION ○
SECTOR DELIMITER +

USCGC POLAR STAR MANEUVERING TRIALS-ANTARCTICA

TEST3 SECTOR No. 3

27 Feb 1985

START SCAN = 1704

STOP SCAN = 2357

AVERAGE SHIP SPEED	3.5	knots
AVERAGE RUDDER ANGLE	13.7	deg (+ve=port)

AVERAGE PORT THRUST	42423	lbs
AVERAGE CENTRE THRUST	65203	lbs
AVERAGE STBD THRUST	77307	lbs

TOTAL THRUST	164933	lbs
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CHANGE IN HEADING	173.340	deg
ELAPSED TIME	671.5	sec
ARC LENGTH	1637.7	meters
RECKONED SPEED	4.7	knots

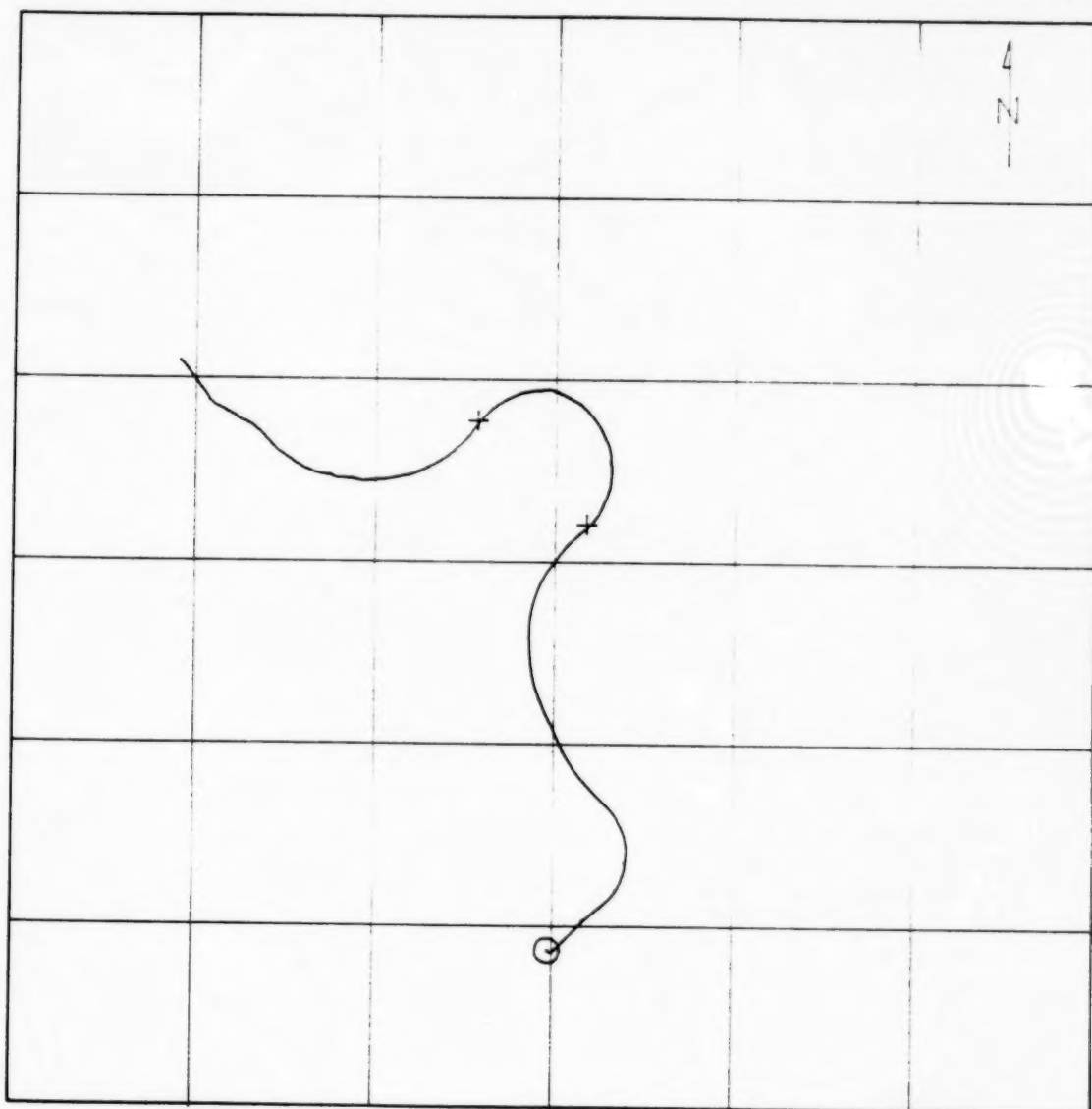
AVERAGE RATE OF HEADING	.2581	deg/sec
TIME TO TURN 180 DEG	11.62	min

TURNING CIRCLE RADIUS	541	meters
TURN CIRCLE RADIUS/LBP	5.04	
TURN CIRCLE RADIUS/WLL	5.26	
TURN CIRCLE DIAMETER	1184	yds

USCGC POLAR STAR
JANUARY 1985 MANOEUVERING TESTS

TEST 3 SECTOR 3

22 Jan 1985



GRID SPACING 1000 meters

START LOCATION ○
SECTOR DELIMITER +

USCGC POLAR STAR MANEUVERING TRIALS-ANTARCTICA

TEST3 SECTOR No. 4

27 Feb 1985

START SCAN = 2443

STOP SCAN = 2561

AVERAGE SHIP SPEED	3.9	knots
AVERAGE RUDDER ANGLE	-25.5	deg (+ve=port)

AVERAGE PORT THRUST	18945	lbs
AVERAGE CENTRE THRUST	66888	lbs
AVERAGE STBD THRUST	91853	lbs

TOTAL THRUST	177686	lbs
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CHANGE IN HEADING	89.190	deg
ELAPSED TIME	537.9	sec
ARC LENGTH	1375.6	meters
RECKONED SPEED	5.0	knots

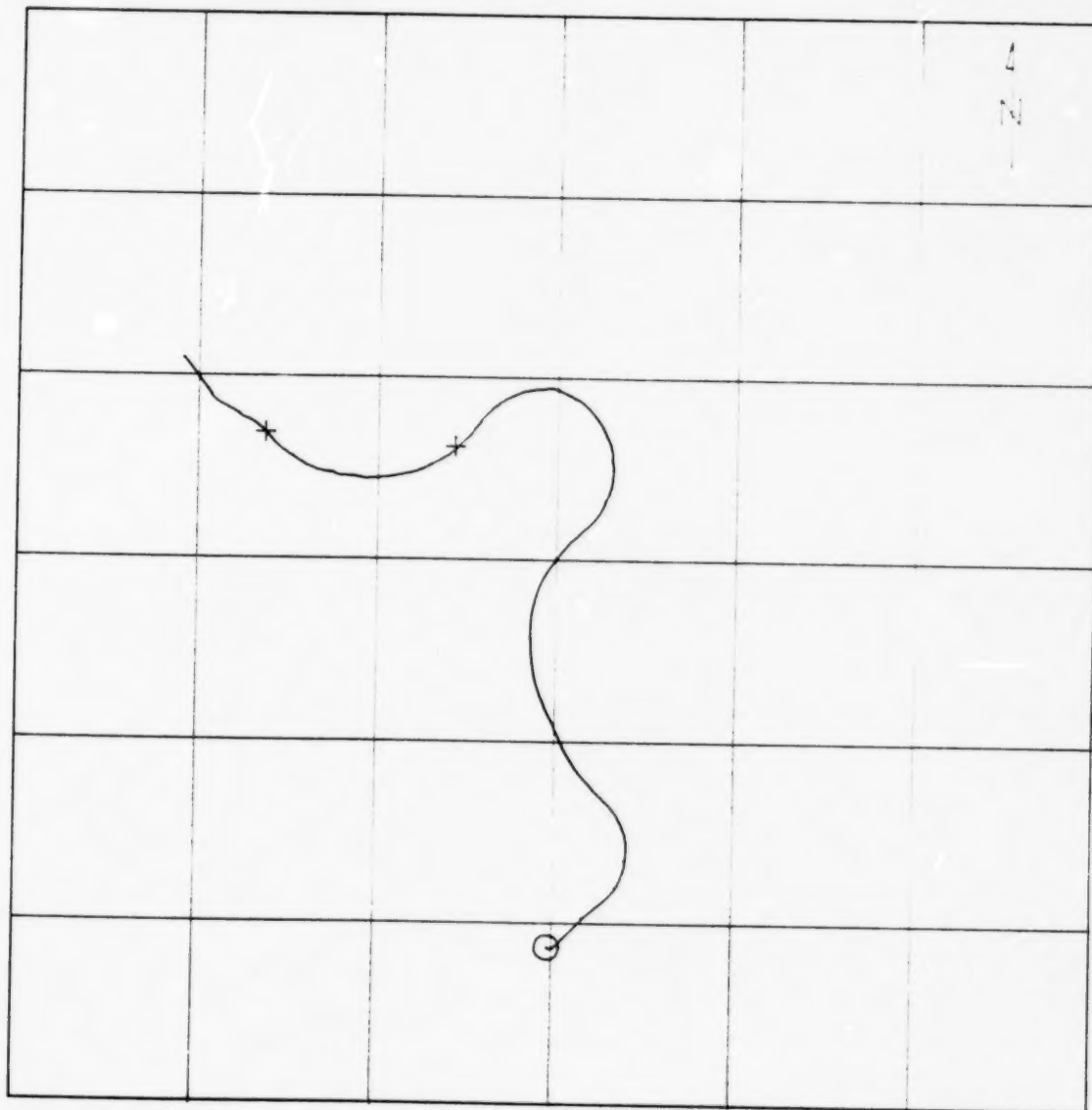
AVERAGE RATE OF HEADING	.1658	deg/sec
TIME TO TURN 180 DEG	18.09	min

TURNING CIRCLE RADIUS	884	meters
TURN CIRCLE RADIUS/LBP	8.24	
TURN CIRCLE RADIUS/WLL	8.59	
TURN CIRCLE DIAMETER	1933	yds

USCGC POLAR STAR
JANUARY 1985 MANOEUVERING TESTS

TEST 3 SECTOR 4

22 Jan 1985



GRID SPACING 1000 meters

START LOCATION ○
SECTOR DELIMITER +

USCSC POLAR STAR MANEUVERING TRIALS-ANTARCTICA

TEST4 SECTOR No. 1

27 Feb 1985

START SCAN = 840

STOP SCAN = 1281

AVERAGE SHIP SPEED	3.5	knots
AVERAGE RUDDER ANGLE	-21.7	deg (+ve=port)
AVERAGE PORT THRUST	9300	lbs
AVERAGE CENTRE THRUST	284246	lbs
AVERAGE STD THRUST	45065	lbs
TOTAL THRUST	338611	lbs

CHANGE IN HEADING	87.876	deg
ELAPSED TIME	429.7	sec
ARC LENGTH	848.5	meters
RECKONED SPEED	3.8	knots

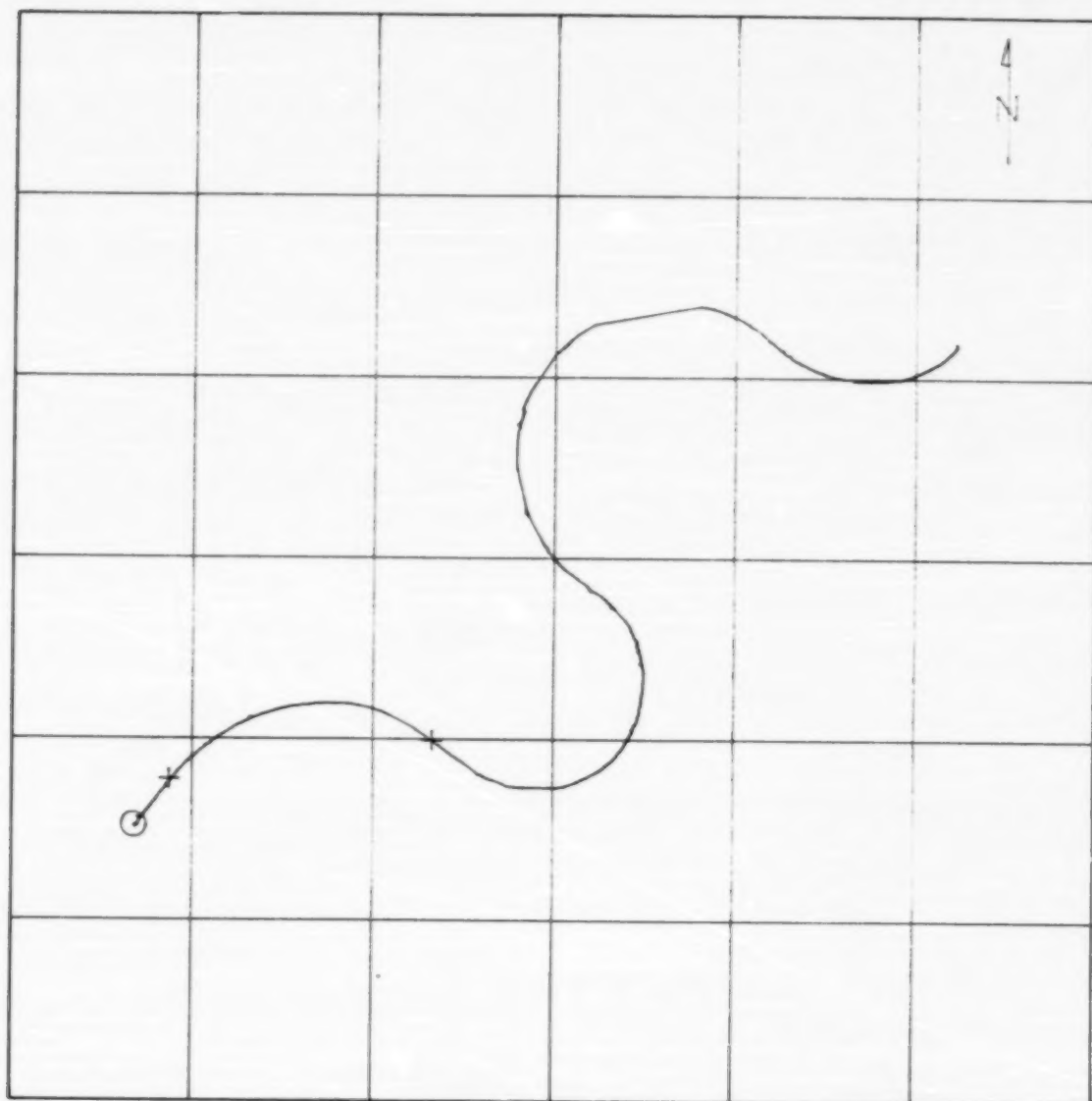
AVERAGE RATE OF HEADING	.2045	deg/sec
TIME TO TURN 180 DEG	14.57	min

TURNING CIRCLE RADIUS	553	meters
TURN CIRCLE RADIUS/LBP	5.16	
TURN CIRCLE RADIUS/WLL	5.38	
TURN CIRCLE DIAMETER	1210	yds

USCGC POLAR STAR
JANUARY 1985 MANOEUVERING TESTS

TEST 4 SECTOR 1

23 Jan 1985



GRID SPACING 500 meters

START LOCATION ○
SECTOR DELIMITER +

USCGC POLAR STAR MANEUVERING TRIALS-ANTARCTICA

TEST 4 SECTOR No. 2

27 Feb 1985

START SCAN = 1378

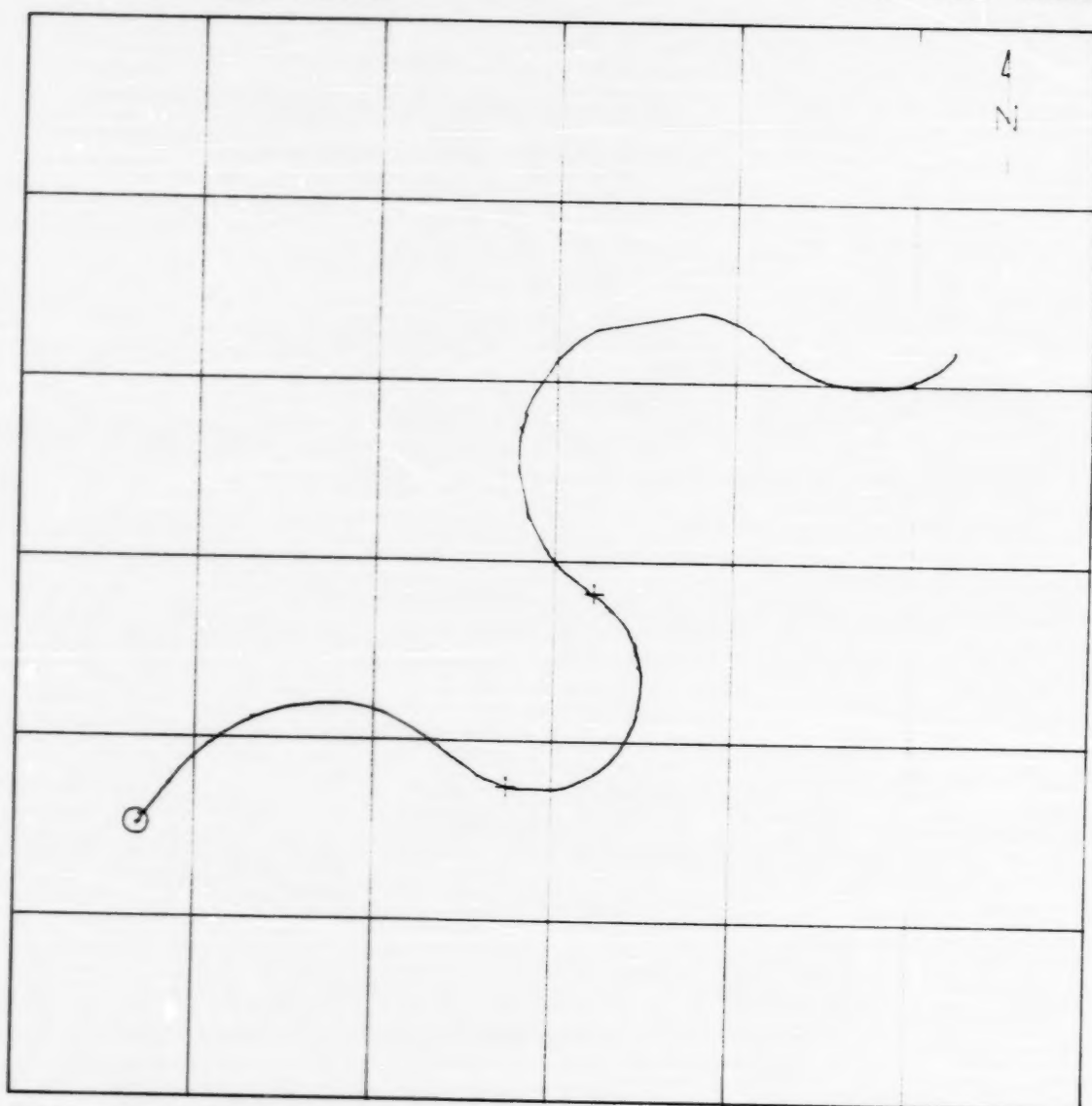
STOP SCAN = 1903

AVERAGE SHIP SPEED	2.4	knots
AVERAGE RUDDER ANGLE	15.1	deg (+ve=port)
AVERAGE PORT THRUST	25916	lbs
AVERAGE CENTRE THRUST	262579	lbs
AVERAGE STD THRUST	-15089	lbs
TOTAL THRUST	273406	lbs
CHANGE IN HEADING	159.552	deg
ELAPSED TIME	572.3	sec
ARC LENGTH	998.3	meters
RECKONED SPEED	3.4	knots
AVERAGE RATE OF HEADING	.2788	deg/sec
TIME TO TURN 180 DEG	10.76	min
TURNING CIRCLE RADIUS	358	meters
TURN CIRCLE RADIUS/LBP	3.34	
TURN CIRCLE RADIUS/WLL	3.48	
TURN CIRCLE DIAMETER	784	yds

USCGC POLAR STAR
JANUARY 1985 MANOEUVERING TESTS

TEST 4 SECTOR 2

23 Jan 1985



GRID SPACING 500 meters

START LOCATION ○
SECTOR DELIMITER +

USCSC POLAR STAR MANEUVERING TRIALS-ANTARCTICA

TEST4 SECTOR No. 3

27 Feb 1985

START SCAN = 1984

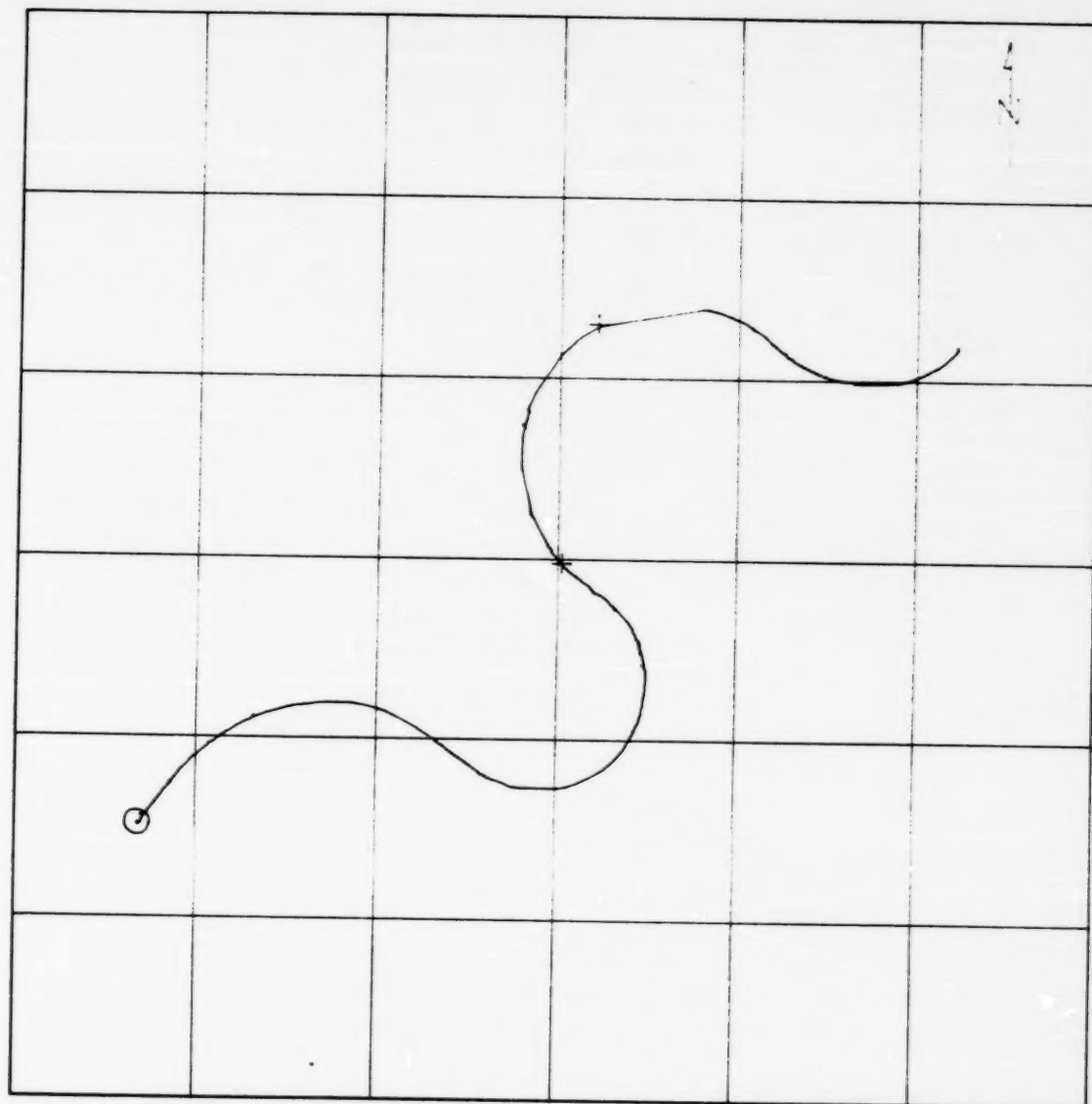
STOP SCAN = 2354

AVERAGE SHIP SPEED	3.6	knots
AVERAGE RUDDER ANGLE	-22.4	deg (+ve=port)
AVERAGE PORT THRUST	7150	lbs
AVERAGE CENTRE THRUST	288218	lbs
AVERAGE STBD THRUST	27891	lbs
TOTAL THRUST	323259	lbs
CHANGE IN HEADING	106.002	deg
ELAPSED TIME	390.2	sec
ARC LENGTH	821.7	meters
RECKONED SPEED	4.1	knots
AVERAGE RATE OF HEADING	.2717	deg/sec
TIME TO TURN 180 DEG	11.04	min
TURNING CIRCLE RADIUS	444	meters
TURN CIRCLE RADIUS/LBP	4.14	
TURN CIRCLE RADIUS/WLL	4.32	
TURN CIRCLE DIAMETER	971	yds

USCGC POLAR STAR
JANUARY 1985 MANOEUVERING TESTS

TEST 4 SECTOR 3

23 Jan 1985



GRID SPACING 500 meters

START LOCATION ○
SECTOR DELIMITER +

USCGC POLAR STAR MANEUVERING TRIALS-ANTARCTICA

TEST: SECTOR No. 4

27 Feb 1985

START SCAN = 2659

STOP SCAN = 2982

AVERAGE SHIP SPEED	2.6	knots
AVERAGE RUDDER ANGLE	10.6	deg (tve=port)

AVERAGE PORT THRUST	29586	lbs
AVERAGE CENTRE THRUST	231406	lbs
AVERAGE STBD THRUST	3058	lbs

TOTAL THRUST	264150	lbs
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CHANGE IN HEADING	80.910	deg
ELAPSED TIME	327.8	sec
ARC LENGTH	569.5	meters
RECKONED SPEED	3.4	knots

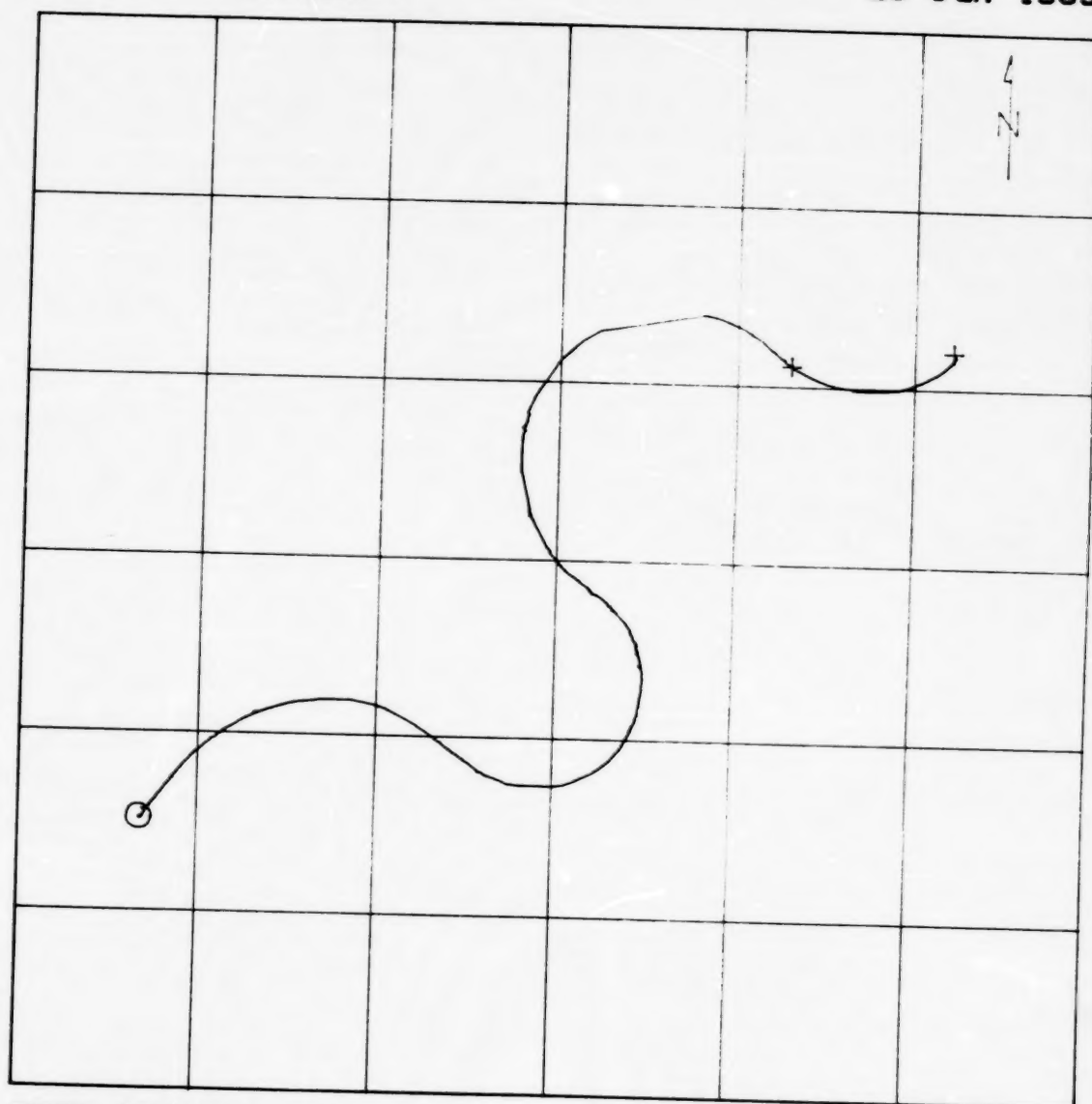
AVERAGE RATE OF HEADING	.2468	deg/sec
TIME TO TURN 180 DEG	12.15	min

TURNING CIRCLE RADIUS	403	meters
TURN CIRCLE RADIUS/LBP	3.76	
TURN CIRCLE RADIUS/WLL	3.92	
TURN CIRCLE DIAMETER	882	yds

USCGC POLAR STAR
JANUARY 1985 MANOEUVERING TESTS

TEST 4 SECTOR 4

23 Jan 1985



GRID SPACING 500 meters

START LOCATION ○
SECTOR DELIMITER +

USCGC POLAR STAR MANEUVERING TRIALS-ANTARCTICA

TESTS SECTOR No. 1

27 Feb 1995

START SCAN = 414

STOP SCAN = 546

AVERAGE SHIP SPEED	3.4	knots
AVERAGE RUDDER ANGLE	19.3	deg (+ve=port)

AVERAGE PORT THRUST	22785	lbs
AVERAGE CENTRE THRUST	249463	lbs
AVERAGE STBD THRUST	683	lbs

TOTAL THRUST	272931	lbs
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CHANGE IN HEADING	91.404	deg
ELAPSED TIME	239.5	sec
ARC LENGTH	504.3	meters
RECKONED SPEED	4.9	knots

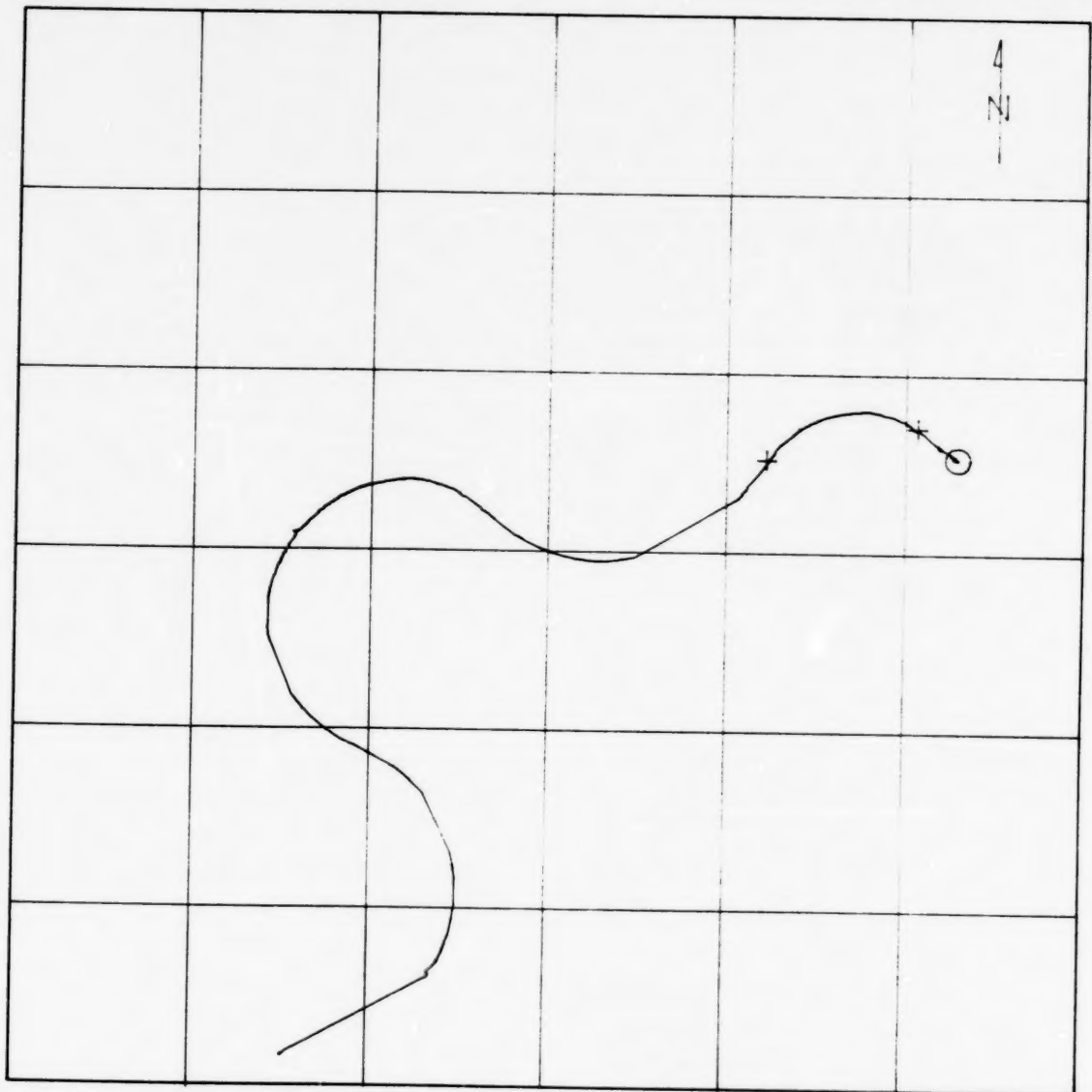
AVERAGE RATE OF HEADING	.3817	deg/sec
TIME TO TURN 180 DEG	7.86	min

TURNING CIRCLE RADIUS	379	meters
TURN CIRCLE RADIUS/LBP	3.53	
TURN CIRCLE RADIUS/WLL	3.68	
TURN CIRCLE DIAMETER	829	yds

USCGC POLAR STAR
JANUARY 1985 MANOEUVERING TESTS

TEST 5 SECTOR 1

23 Jan 1985



GRID SPACING 500 meters

START LOCATION ○
SECTOR DELIMITER +

USCSC POLAR STAR MANEUVERING TRIALS-ANTARCTICA

TESTS SECTOR No. 2

27 Feb 1985

START SCAN = 867

STOP SCAN = 1040

AVERAGE SHIP SPEED	3.5	knots
AVERAGE RUDDER ANGLE	-19.0	deg (+ve=port)

AVERAGE PORT THRUST	9417	lbs
AVERAGE CENTRE THRUST	279100	lbs
AVERAGE STBD THRUST	36625	lbs

TOTAL THRUST	325142	lbs
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CHANGE IN HEADING	42.300	deg
ELAPSED TIME	175.5	sec
ARC LENGTH	402.3	meters
RECKONED SPEED	4.5	knots

AVERAGE RATE OF HEADING	.2411	deg/sec
TIME TO TURN 180 DEG	12.44	min

TURNING CIRCLE RADIUS	545	meters
TURN CIRCLE RADIUS/LBP	5.08	
TURN CIRCLE RADIUS/WLL	5.30	
TURN CIRCLE DIAMETER	1192	yds

TEST 5 SECTOR 2

A hand-drawn graph on a 6x6 grid. The curve starts at the bottom left, rises to a peak, dips to a local minimum, and then rises again to a higher peak. The curve is marked with several points and crosses.

START LOCATION	○
SECTOR DELIMITER	+

USCGC POLAR STAR MANEUVERING TRIALS-ANTARCTICA

TESTS SECTOR No. 3

27 Feb 1985

START SCAN = 1118

STOP SCAN = 1505

AVERAGE SHIP SPEED	3.4	knots
AVERAGE RUDDER ANGLE	13.6	deg (+ve=port)

AVERAGE PORT THRUST	17078	lbs
AVERAGE CENTRE THRUST	256477	lbs
AVERAGE STBD THRUST	927	lbs

TOTAL THRUST	274481	lbs
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CHANGE IN HEADING	132.984	deg
ELAPSED TIME	397.0	sec
ARC LENGTH	984.4	meters
RECKONED SPEED	4.8	knots

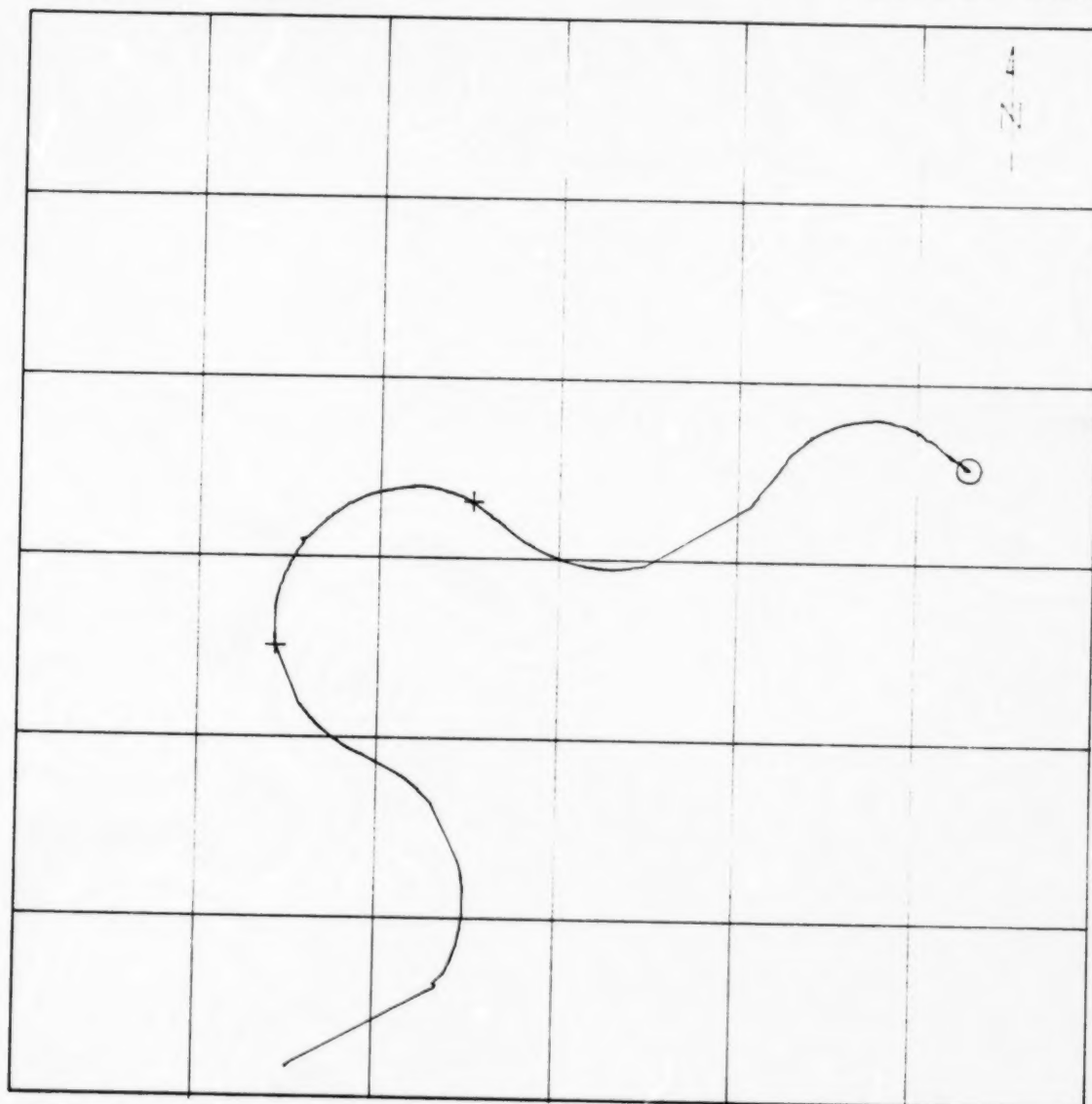
AVERAGE RATE OF HEADING	.3350	deg/sec
TIME TO TURN 180 DEG	8.96	min

TURNING CIRCLE RADIUS	424	meters
TURN CIRCLE RADIUS/LBP	3.95	
TURN CIRCLE RADIUS/WLL	4.12	
TURN CIRCLE DIAMETER	928	yds

USCGC POLAR STAR
JANUARY 1985 MANOEUVERING TESTS

TEST 5 SECTOR 3

23 Jan 1985



GRID SPACING 500 meters

START LOCATION
SECTOR DELIMITER

○
+

USCSC POLAR STAR MANEUVERING TRIALS-ANTARCTICA

TESTS SECTOR No. 4

27 Feb 1985

START SCAN = 1948

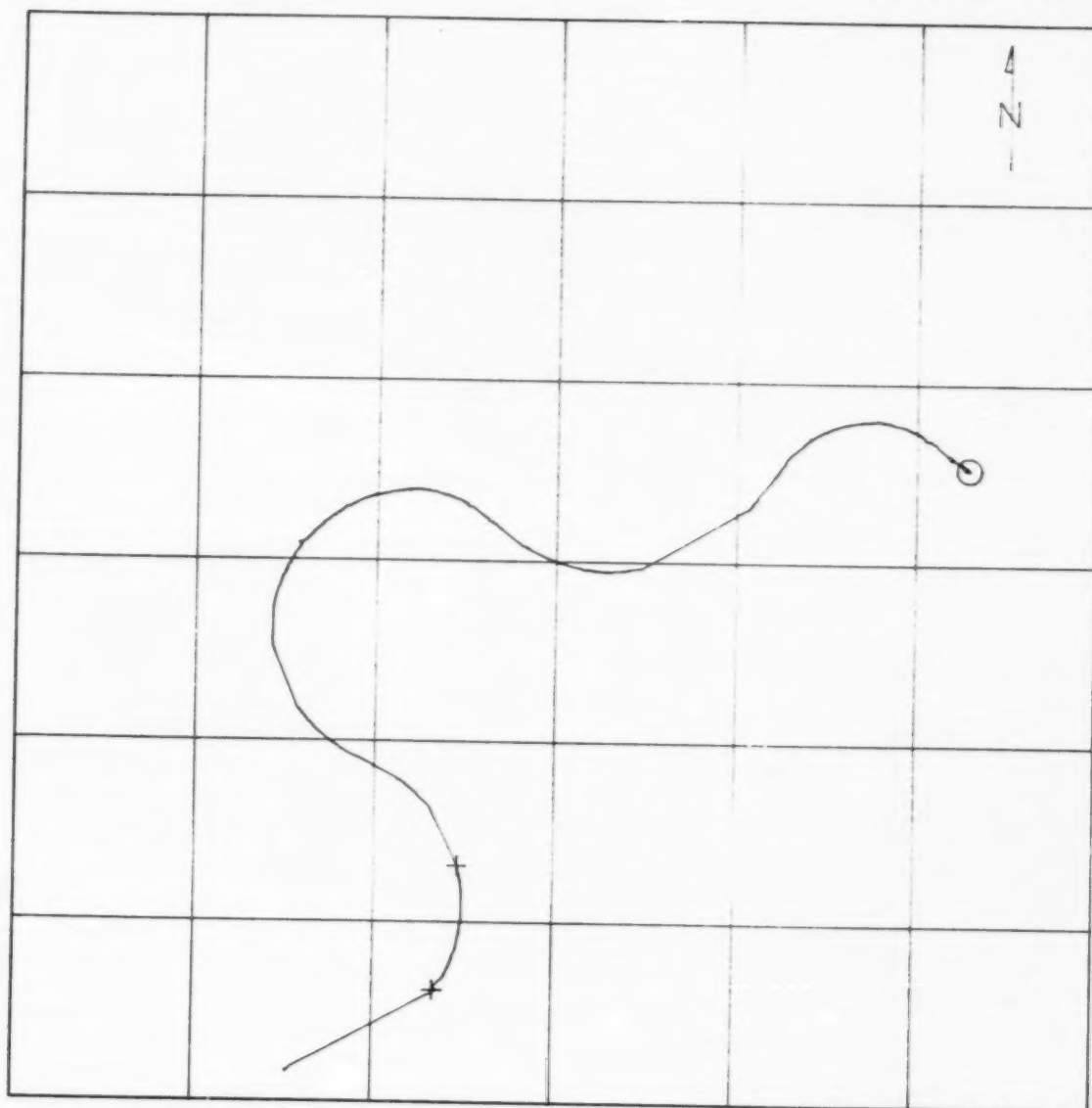
STOP SCAN = 2111

AVERAGE SHIP SPEED	4.0	knots
AVERAGE RUDDER ANGLE	-18.3	deg (+ve=port)
AVERAGE PORT THRUST	9349	lbs
AVERAGE CENTRE THRUST	286343	lbs
AVERAGE STBD THRUST	31264	lbs
TOTAL THRUST	326956	lbs
CHANGE IN HEADING	47.790	deg
ELAPSED TIME	166.8	sec
ARC LENGTH	374.3	meters
RECKONED SPEED	4.4	knots
AVERAGE RATE OF HEADING	.2865	deg/sec
TIME TO TURN 180 DEG	10.47	min
TURNING CIRCLE RADIUS	449	meters
TURN CIRCLE RADIUS/LBP	4.18	
TURN CIRCLE RADIUS/WLL	4.36	
TURN CIRCLE DIAMETER	982	yds

USCGC POLAR STAR
JANUARY 1985 MANOEUVERING TESTS

TEST 5 SECTOR 4

23 Jan 1985

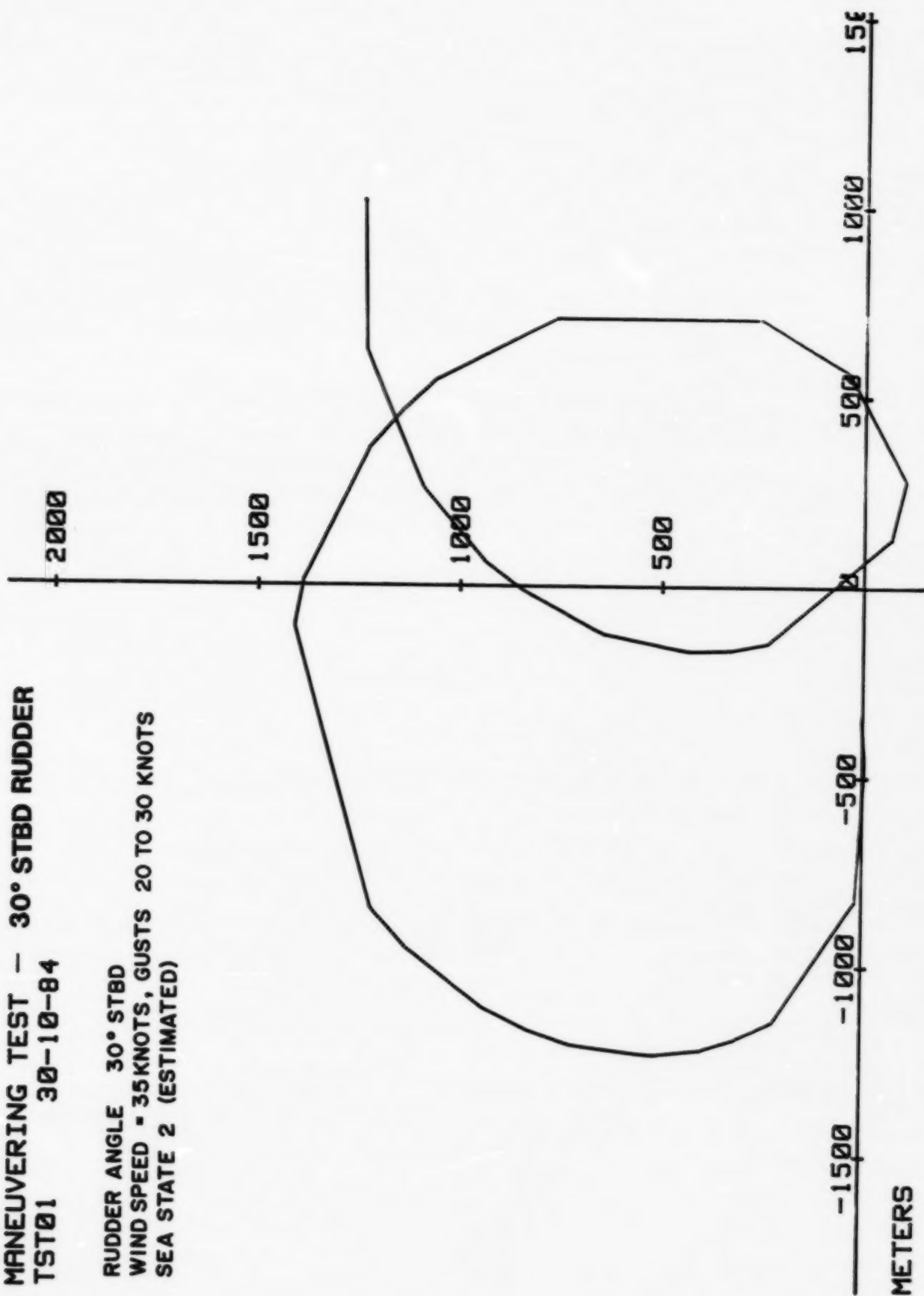


GRID SPACING 500 meters

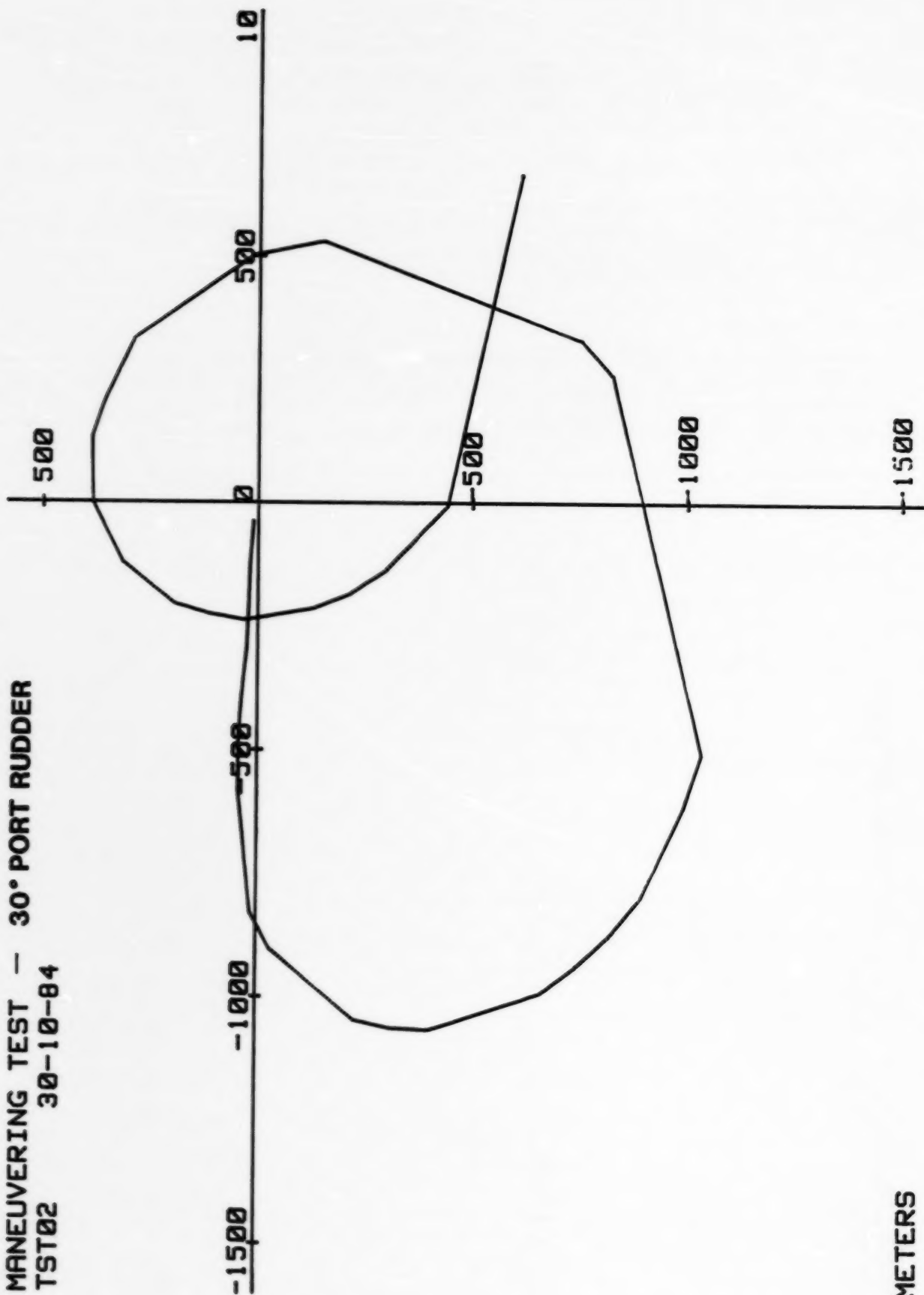
START LOCATION ○
SECTOR DELIMITER +

MANEUVERING TEST - 30° STBD RUDDER
TST01 30-10-84

RUDDER ANGLE 30° STBD
WIND SPEED = 35 KNOTS, GUSTS 20 TO 30 KNOTS
SEA STATE 2 (ESTIMATED)

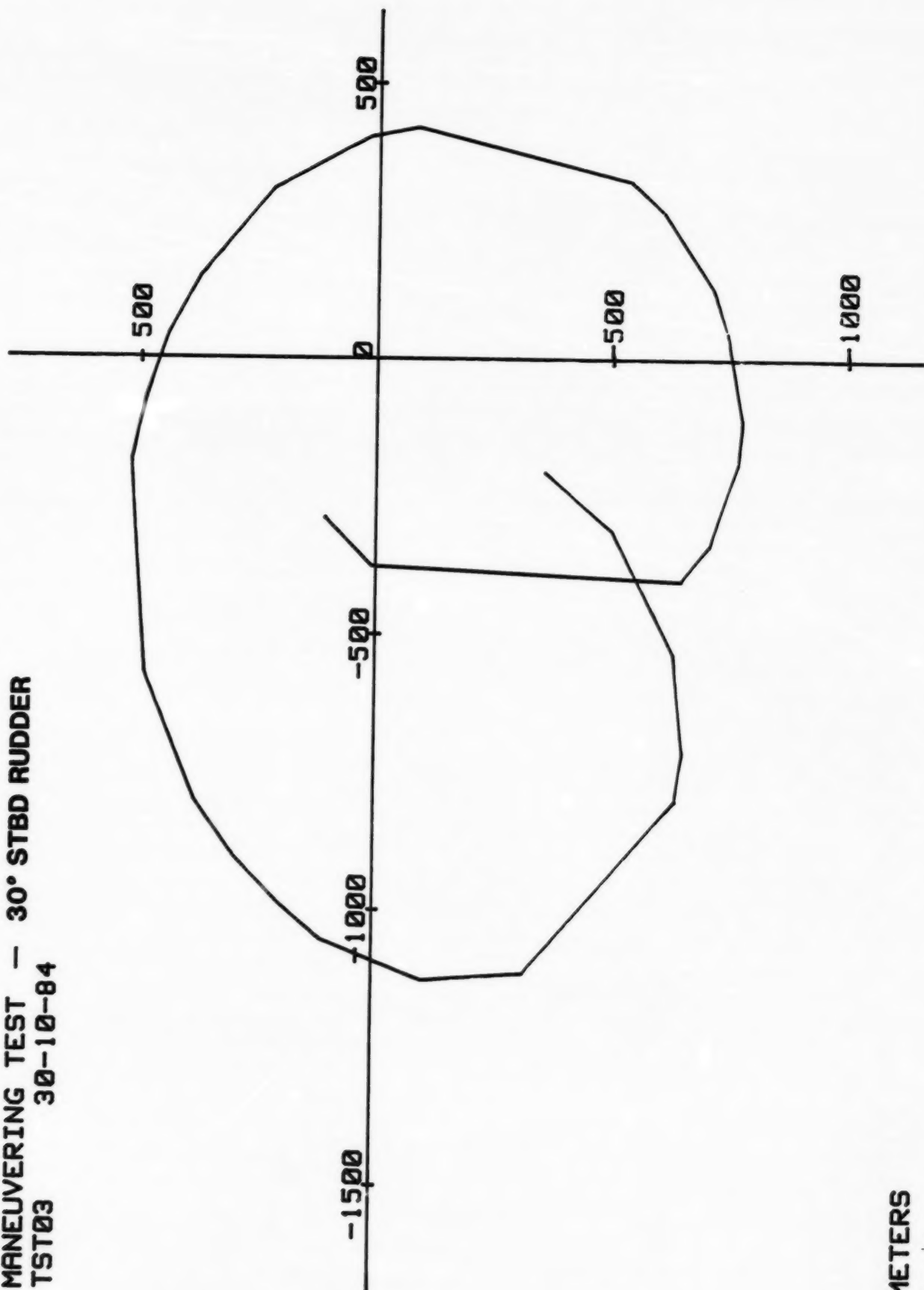


MANEUVERING TEST -- 30° PORT RUDDER
TST02 30-10-84



METERS

MANEUVERING TEST — 30° STBD RUDDER
TST03 30-10-84



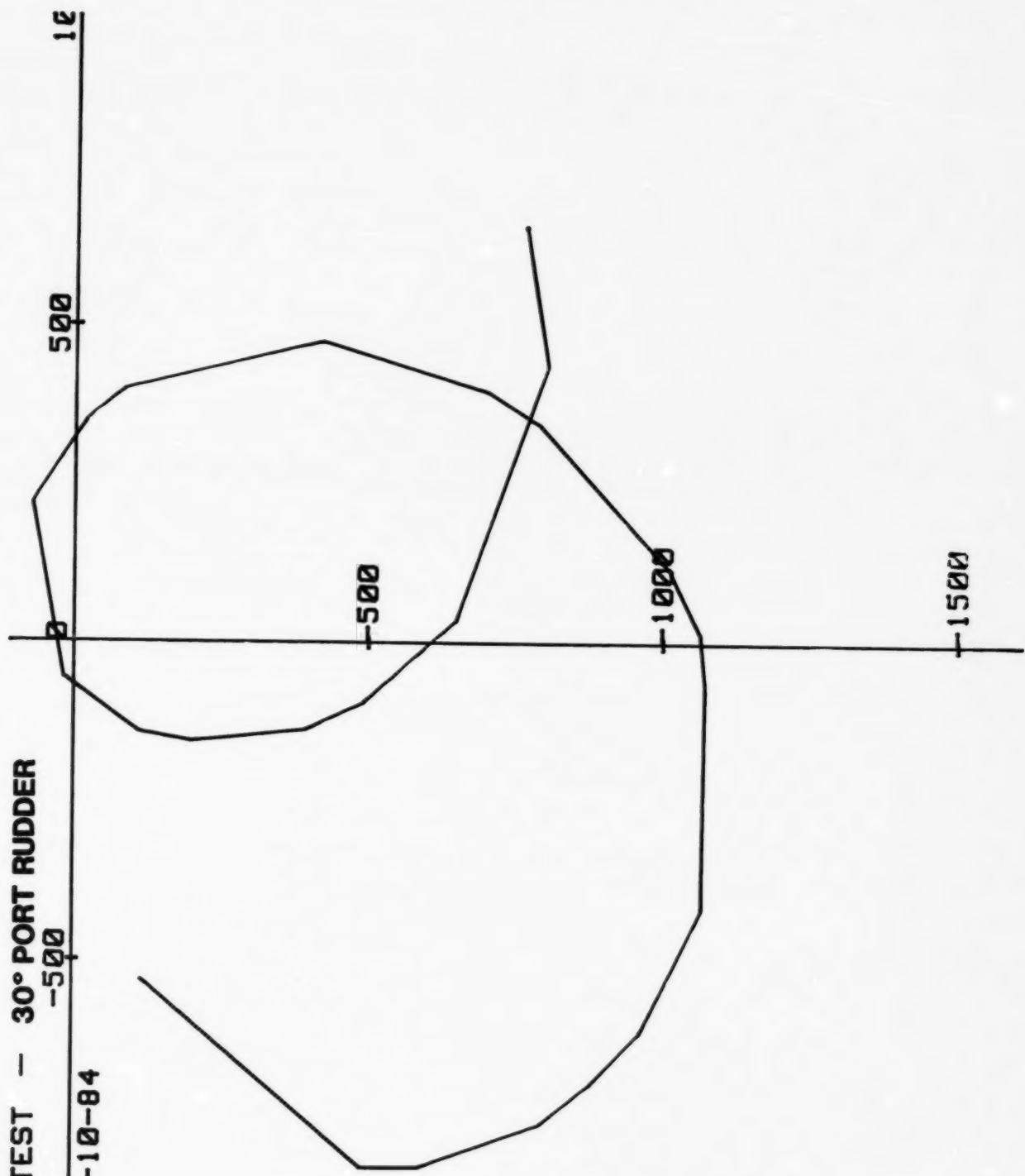
METERS

MANEUVERING TEST - 30° PORT RUDDER

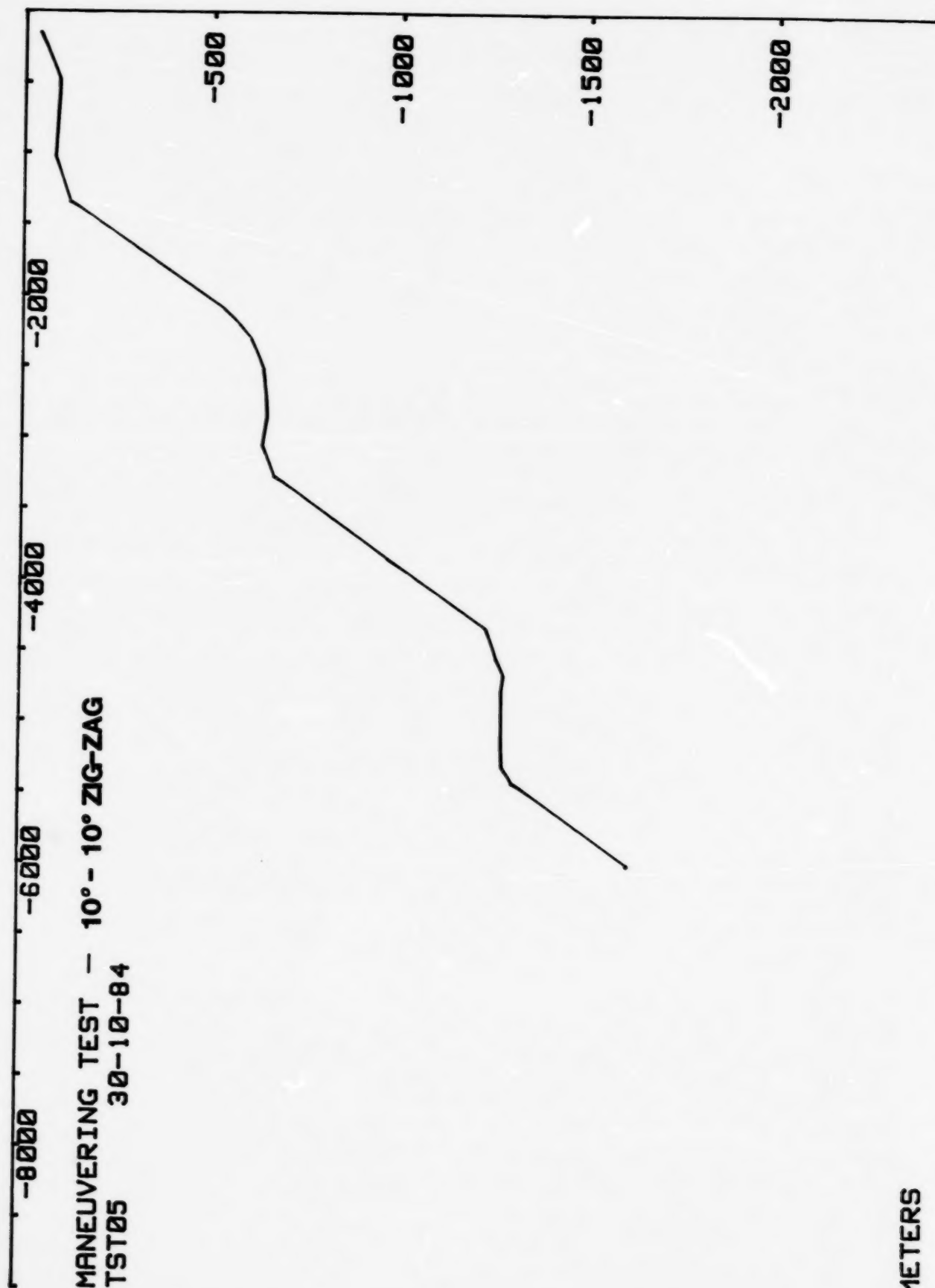
-1000

-500

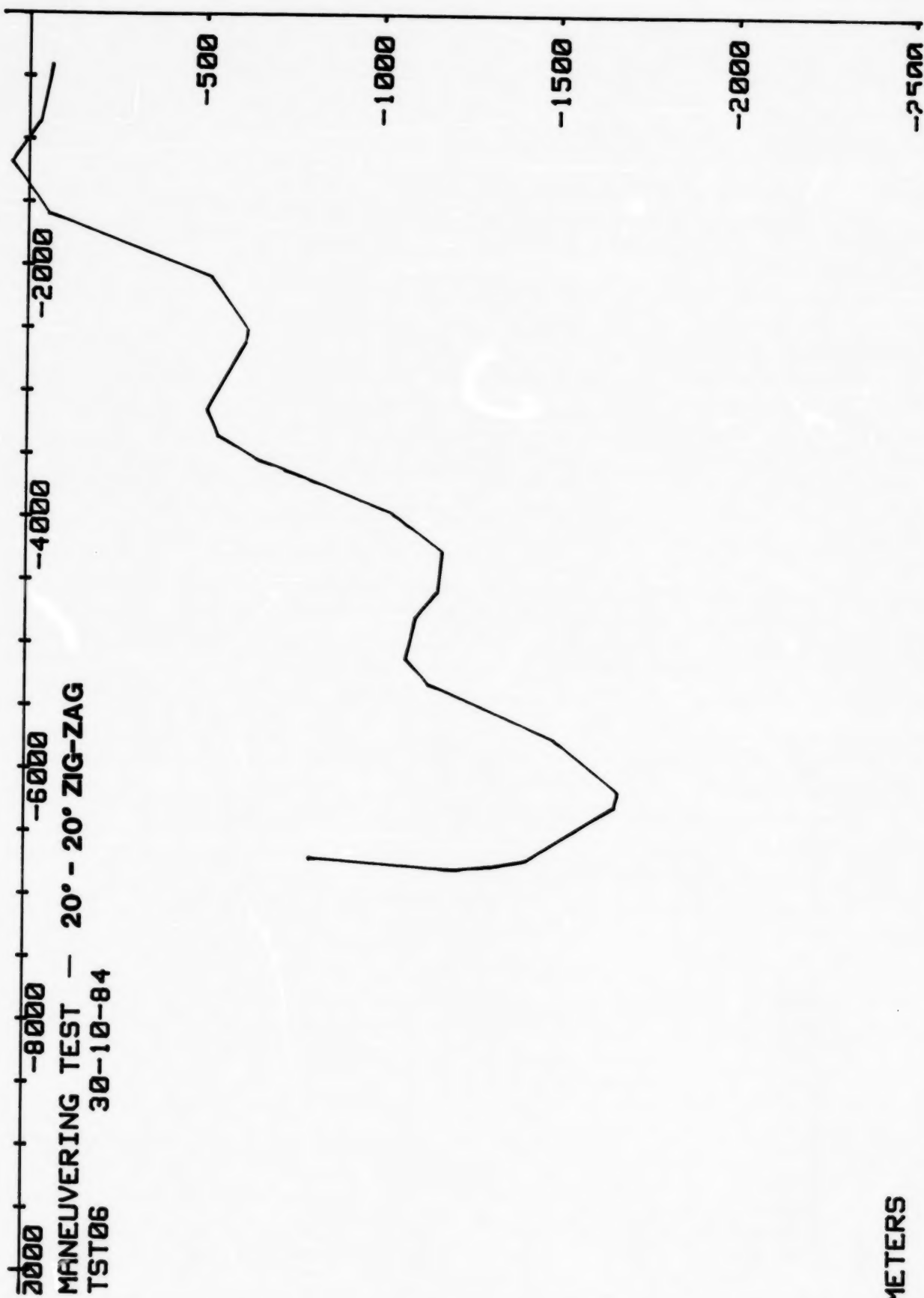
TST04 30-10-84



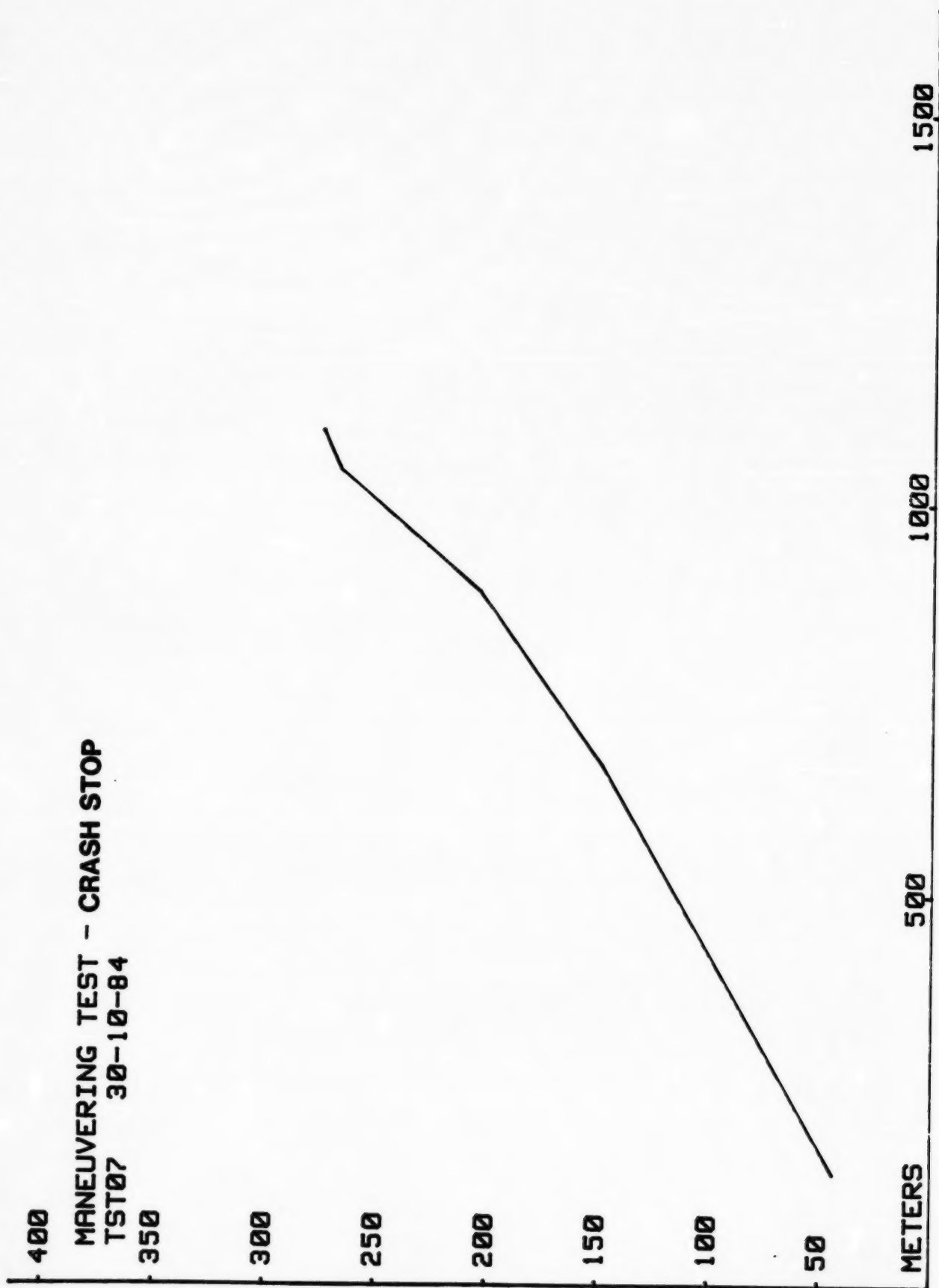
METERS



METERS



MANEUVERING TEST - CRASH STOP
TST07 30-10-84



APPENDIX E

WORK STATEMENT

APPENDIX E
WORK STATEMENT

5.5 Task B - Antarctic Deployment - USCGC POLAR STAR - Manoeuvring Tests

This task relates to carrying out manoeuvring tests in uniform level ice in McMurdo Sound in January 1985.

5.5.1 Program Planning & Management

A comprehensive plan is to be developed in close cooperation with US Authorities and their contractor. Initial plans and budgets specified in paragraph 5.1 are to be updated and notified to the Scientific Authority as the project develops.

5.5.2 Develop Manoeuvring Model

The contractor is to develop a manoeuvring performance predictor model to be used and evaluated in conjunction with the full scale test programs. It is to be based on traditional manoeuvring equation forms based on model tests, as presented in previous reports to TDC.

The model is to be developed on computing hardware suitable for running on board prior to performance of manoeuvring testing.

5.5.3 Assemble and Install Instrumentation Aboard USCGC POLAR STAR

The instrumentation required for this project will be required to record:

- o Rigid Body Motions
- o Rudder Angle (command and actual)
- o Heel Angle
- o Ship's Heading
- o Rudder Torque
- o Ship's Speed (Doppler-Shift Radar)
- o Thrust (3 Shafts)
- o RPM (3 Shafts)
- o Drift Angle
- o Position of Vessel
- o Centre of Yaw rotation

The system is to be integrated with that required to measure ice-breaking dynamics by the U.S. contractor and redundancy is to be ensured.

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The system is to be designed to permit real-time onboard data reduction and near real-time analysis.

In addition to the above, a 35 mm camera with 'databack' and/or video will be attached to a radar repeater to record ship position and broken ice track in turns. This will be affixed to a bridge radar repeater to assess ship global position and attitude. In order to record ice/ship contact conditions, two video systems are to be deployed onboard. These will be portable and used to record simultaneous ship/ice contact. Time synchronization is desirable.

In order to ensure accurate measurement of ship speed in turns, two separate Doppler Systems are to be included. To track the ship globally, a Positioning System is to be deployed. A system of measuring drift angle is also to be incorporated.

All equipment is to be installed aboard the ship in Seattle and bolted to existing brackets or epoxied in place so that no welding or deck/bulkhead penetrations will be required. All system calibrations, tests, etc. are to be conducted prior to departure.

5.5.4 Conduct Ship Manoeuvring Tests

The contractor is to provide up to two experienced and qualified personnel to conduct the tests during the Antarctic deployment.

Data is to be collected onboard during January 1985. The manoeuvring tests are to be conducted in accordance with accepted standards modified to accommodate ice behavior; and in accordance with the agreed test plan.

- o Turning rate at constant helm angles, constant thrust in level ice
- o With ship upright and heeled
- o Use of shafts in turning
- o Backing and filling
- o Breaking out of the channel.

After a suitable test area has been located, the ship will be positioned at the edge of the site on a heading which permits maximum use of the area for testing.

The measurement and control processor, computer, storage devices, and I/O devices are to meet the requirements for real-time data sampling and onboard analysis. Software is to be provided which controls data sampling and permits output of reduced data. In addition, the system is to be capable of analyzing ice properties.

Comparison of math model predictions and actual performance is to be made on a daily basis and used to refine the test plan.

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5.5.5 Reduction and Analysis of Data

Onboard, first-pass data and reduction and analysis is to consist of reducing all test data to engineering units and maintaining running plots of results to ensure that tests are properly conducted and to facilitate planning of subsequent tests. Second-pass data analysis is to be conducted after all testing is complete.

The measured capabilities of the POLAR STAR will be compared with the requirements set-up in the design specifications and with predicted performance. Rationalizing of differences is to be made. In addition, the performance of the POLAR STAR is to be compared with other full scale icebreaker manoeuvring trials for which data is available. Using a non-dimensional basis, a preliminary assessment is to be made of the effect of rudder/propeller configurations.

The information collected during "backing and filling" turns is to be analyzed to determine the effectiveness of this operation, the parameters of significance, and the optimum operating goals.

The effect of heel angle on turning performance is to be investigated. Evaluation of the math modeling prediction techniques is to be made, and conclusions drawn as to their suitability and future development needs.

5.5.6 Level Ice Resistance & Dynamics, etc.

As far as time is available after priority attention to manoeuvring tests, level ice resistance and dynamics testing will be observed and assisted.

5.5.7 Reporting

The contractor is to prepare a draft, final and summary reports. The manoeuvring performance study will constitute a separate volume from other aspects of the Antarctic deployment. On completion of the project, provision is to be made for a presentation to Canadian sponsors.